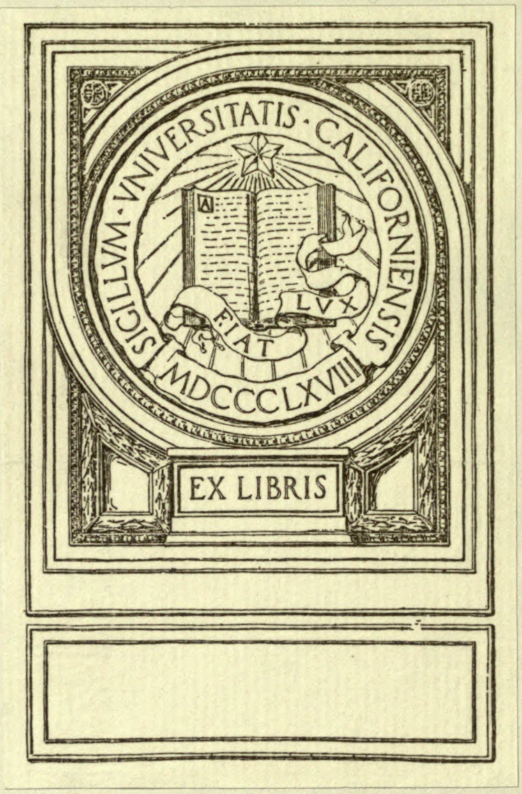
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PUBLICATIONS OF THE YERKES OBSERVATORY

VOLUME III PART I

THE RUMFORD SPECTROHELIOGRAPH OF THE YERKES OBSERVATORY

BY

GEORGE E. HALE
AND
FERDINAND ELLERMAN

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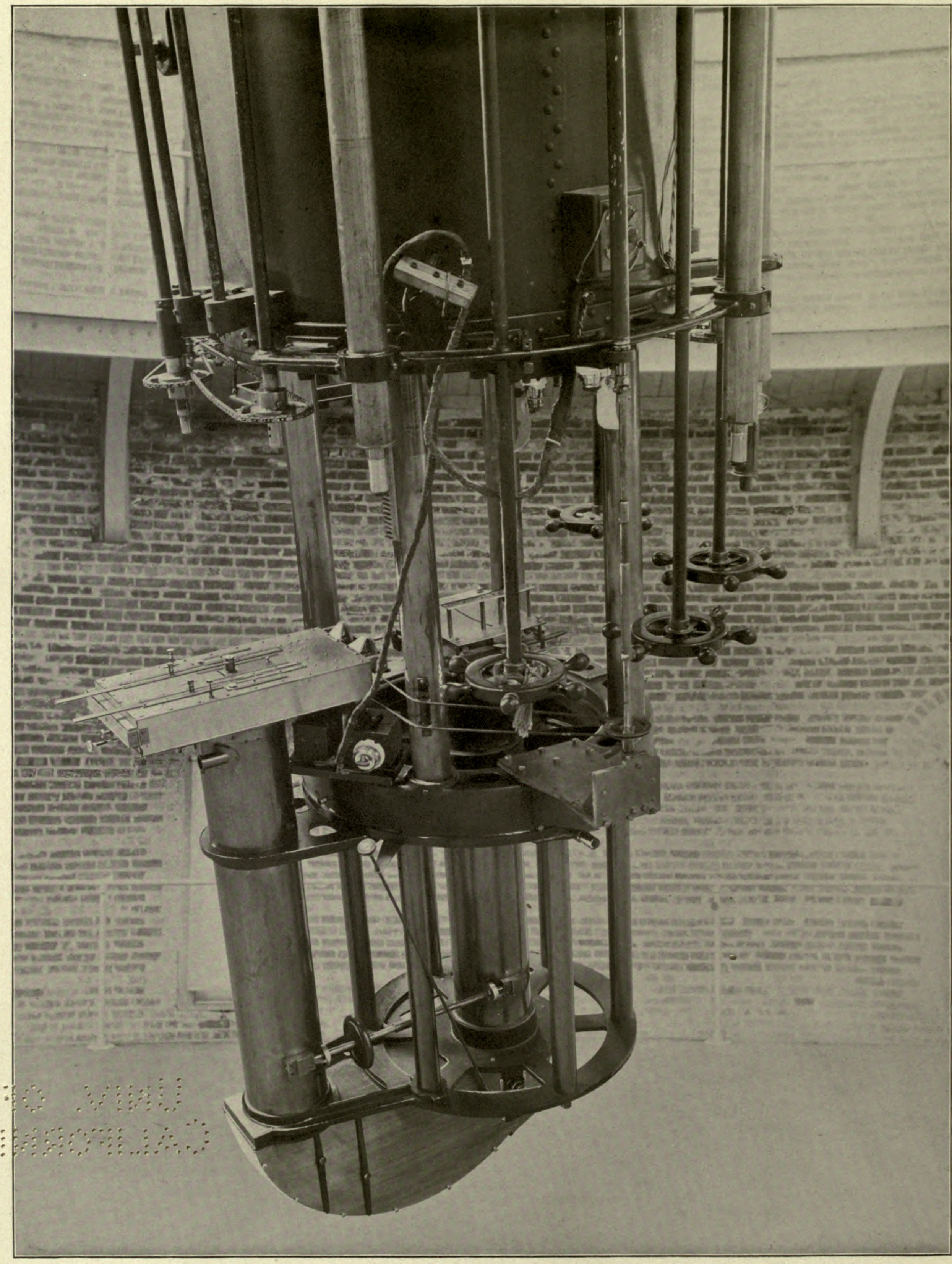
PLATE I



THE RUMFORD SPECTROHELIOGRAPH ATTACHED TO THE 40-INCH YERKES REFRACTOR

THE RUMFORD SPECTROHELIOGRAPH OF THE YERKES OBSERVATORY

By George E. Hale and Ferdinand Ellerman[1]

INTRODUCTION

The application of the spectroscope in 1868 to the observation of solar prominences in full sunlight opened an extensive field of research, and directed the attention of astronomers to the importance of applying the powerful instruments and methods of the physical laboratory to the study of the Sun. Since that time the rise and development of stellar spectroscopy have further emphasized the importance of solar investigation. For it cannot be too often repeated that the Sun is the only star whose phenomena can be studied in detail; in interpreting the spectroscopic phenomena of all the other stars we must therefore return in every instance to the Sun. If its infinitely varied and complex activities were well understood, the problems encountered in the study of stellar evolution would be greatly simplified. But although the constant use of the spectroscope, dating back to the discovery of the chemical constitution of the Sun in 1859, has furnished an immense amount of valuable information, there appears to be an exceptional opportunity at the present time to secure new and important results, especially through the use of the large spectroscopes and other powerful instruments of the physical laboratory. For solar spectroscopy has by no means kept pace with laboratory spectroscopy; few large grating spectroscopes, such as are found in every physical laboratory, have ever been employed to study a large image of the Sun. This being true, it is less remarkable that other laboratory instruments, not so generally available, are still awaiting application in solar research.

The widespread interest in total solar eclipses, and the great expenditure of time and money so freely made in observing them, surely tend to emphasize what has been said. For if it is worth while (as it certainly is) to travel thousands of miles, and to undergo hardships, in order to spend a few flying seconds in making observations, it would seem no less advantageous to continue solar work at home, where entirely new phenomena can be observed daily with a much smaller expenditure of effort. Total eclipses of the Sun will always be of great importance, as the corona cannot be observed in full sunlight. But the study of many other solar phenomena, which can be observed whenever the sky is clear, is quite as likely to advance our knowledge of the solar constitution.

It was with some such ideas in mind that the work of the Kenwood Observatory was undertaken in 1888. It seemed obvious that even a very slight appreciation of the subject should suffice to render possible some improvements of method. A first step in this direction was attempted by the invention of the spectroheliograph in 1889. The original purpose of this instrument was the photography of the chromosphere and prominences, in order to simplify and render more accurate the daily delineation of their form. It was subsequently found, as will be shown in the present paper, that the instrument had a far wider range of application, and that it could be applied in directions which had not suggested themselves in 1889.

The principle of the spectroheliograph is exceedingly simple. Imagine a direct-vision spectroscope in which the eyepiece ordinarily employed is replaced by a (second) slit. If an image of the Sun is formed on the first slit of this spectroscope, the second slit will permit the passage of only a narrow region of the spectrum corresponding in width to this slit. If the slit is now moved until it

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[1] Although this paper has been written by myself, for convenience of reference to previous studies and opinions, it belongs also to Mr. Ellerman, because of his important share in the work.— G. E. H.

coincides with the $H\beta$ line, for example, only hydrogen light will pass through the instrument. If, then, a photographic plate is placed behind and almost in contact with the second slit, and the spectroscope is moved at right angles to its optical axis, an image of the Sun, in monochromatic hydrogen light, will be built up on the plate from the successive images of the slit. If the exposure is suitable, the chromosphere and prominences will be shown surrounding this image.

Such is the spectroheliograph in its simplest form. It is obviously immaterial whether the motion be given to the spectroscope, on the one hand, or to the solar image and photographic plate, on the other. It is only necessary that the relative motion of the solar image and first slit be such that light from all parts of the solar disk shall pass successively through the slit, while the photographic plate and second slit experience a corresponding relative motion. The second slit serves simply to isolate any desired line in the spectrum ; hence its width must be such as exactly to include this line, and to exclude all light from other parts of the spectrum. It is evident that the spectroheliograph may be considered simply as a form of monochromatic exposing shutter, differing from the ordinary focal plane shutter only through the use of a narrower exposing slit, and the inclusion of an optical train which limits the light to a single line in the spectrum.

Although this idea suggested itself to me quite independently in 1889, I subsequently learned that the principle was by no means new. Indeed, Janssen had suggested it as early as 1869, while Braun, of Kalocsa, and Lohse, of Potsdam, had designed instruments involving the same principle in 1872 and 1880 respectively. Indeed, Lohse had constructed and experimented with the instrument he designed, but his work was not successful. This may have been due in part to the fact that the hydrogen line which he employed is not nearly so well adapted for prominence photography as are the H and K lines of calcium. This was one of the difficulties experienced in my first (unsuccessful) experiments, which, through the kindness of Professor Pickering, were made at the Harvard College Observatory in the winter of 1889–90.

In April, 1891, after the Kenwood Observatory had been equipped with a twelve-inch equatorial refractor and a powerful solar spectroscope, a photographic study of the ultra-violet spectrum of the chromosphere and prominences was undertaken in the hope of finding lines better adapted than those of hydrogen for the photography of the prominences. The brilliant H and K lines of calcium, previously observed visually in full sunlight by Professor Young and photographically at total eclipses, were found in all cases to be the most conspicuous lines in the spectrum of the chromosphere and prominences. The remarkable brightness of these lines, and more particularly their position at the center of the broad dark shades due to the denser calcium vapor in the lower portion of the solar atmosphere, render them peculiarly well adapted for the purposes of prominence photography. Indeed, it was possible with their aid to obtain good photographs of single prominences merely by opening the slit of the spectroscope to such an extent as to include a considerable part of the prominence, and giving a very short exposure to the image formed directly upon a photographic plate. But this method was too limited to be of general application. In order to record photographically the entire circumference of the Sun, with the chromosphere and prominences, it was necessary to employ the principle of the spectroheliograph, involving the use of narrow slits, moved with reference to the solar image and photographic plate. The first successful spectroheliograph was brought into use at the Kenwood Observatory in January, 1892. After this time it was employed regularly on every clear day until May 1895, soon after which the instruments of the Kenwood Observatory were removed to the Yerkes Observatory.

My spectroscopic studies of the Sun during the spring and summer of 1891 were not confined to the chromosphere and prominences. It was soon found that the H and K lines, previously recognized as no less characteristic of the prominences than the hydrogen lines themselves, were reversed from dark to bright in regions scattered all over the solar disk. This fact had not escaped the attention of Professor Young, who had long before remarked the presence of these lines in the neighborhood of active Sun-spots. But the greater delicacy of the photographic process showed these bright lines to characterize very extensive regions on the Sun's surface, not confined to the immediate neighborhood of spots, but scattered throughout the Sun-spot zones, and even extending from pole to pole. It was noticed from the outset that these bright regions corresponded closely with the well-known faculæ, and in my earlier work they were called by this name. It has since become clear, however, that a distinctive term should be adopted, and I now propose the name *flocculi* for the regions on the Sun's disk which are shown only on photographs made with the spectroheliograph (see p. 14).

The possibility of photographing these bright regions on the Sun's disk with the spectroheliograph at once greatly extended the range of that instrument, as it was thus shown to be capable of recording, not only the prominences, which could be observed, though very laboriously, by visual methods, but also extensive and important phenomena invisible to the eye and not shown on photographs taken in the ordinary manner. Spectroheliographs were accordingly adopted for use at other observatories, first by Mr. Evershed in England, and subsequently (in 1893) by M. Deslandres at the Paris Observatory. Both of these spectroscopists introduced modifications and improvements of the instrument—Mr. Evershed constructing a direct-vision spectroheliograph of remarkable simplicity and beauty, and M. Deslandres, with a different type of instrument, obtaining photographs of great excellence.

Certain defects of construction in the Kenwood spectroheliograph, which nevertheless did not prevent it from yielding some thousands of photographs of prominences and calcium flocculi, were incident to the circumstances which governed the design of the instrument. For the earlier experiments in solar-prominence photography, a large plane grating spectroscope had been constructed, with collimator and observing telescope rigidly fixed at an angle of twenty-five degrees. The simplest and best form of spectroheliograph, first illustrated by the instrument used in my experiments on Mount Etna in 1894,[2] is that in which the whole instrument moves as a single structure, the solar image and photographic plate being fixed in position. The large size of the Kenwood solar spectroscope, and the necessity of attaching it rigidly and without means of motion to the twelve-inch refractor, precluded the possibility of employing this principle. It was accordingly decided to adopt, as the best means available under the circumstances, a pair of moving slits, one at the extremity of the collimator, the other at the end of the observing telescope, immediately in front of the photographic plate. Thus while the first slit was moved (by hydraulic power) across the fixed solar image, the second slit, connected with the first slit by a system of levers, was moved with the spectrum at such a rate that the K line continued to pass through it, building up a monochromatic image of the Sun on the photographic plate. It is obvious that under these circumstances the motion of the K line (usually in the fourth-order spectrum) would not have the same velocity as the first slit. This resulted in a compression of the solar image, afterward eliminated by a simultaneous motion of the photographic plate, which was displaced during the exposure by an amount equal to the difference between the long and short axes of the oval image of the Sun.

It had been hoped and expected that the interruption in the daily series of photographs caused by removal to the Yerkes Observatory in 1896 would be of short duration; but unfortunately this did not prove to be the case. The twelve-inch refractor, devoted at Kenwood entirely to solar work, was needed at the Yerkes Observatory for general purposes. It therefore became necessary to remove the spectroheliograph from this telescope, and to modify the mounting in order to adapt it for general observational work. The spectroheliograph was remodeled for use with the forty-inch refractor as a solar spectroscope, and it was expected that a new spectroheliograph, large enough to photograph the seven-inch (17.8 cm) image at the focus of this telescope, would soon be ready for use. But the funds required for the construction of the new spectroheliograph were not forthcoming, and when it finally became possible to undertake work on this instrument (through a grant from the Rumford

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[2] *Astronomy and Astrophysics*, 1894.

Fund, and the gifts of friends of the Observatory) progress was slow, owing to the limited funds available. For a seven-inch solar image, collimator and camera lenses of about ten inches (25.4 cm) aperture were needed; but the considerable cost of such lenses rendered their purchase impossible, and a pair of 6¼-inch (15.7 cm) Voigtländer portrait lenses, obtained from second-hand dealers after a year's search, were adopted. With lenses of this aperture it is evident that much light must be lost at the extremities of the slit, and that the resulting image of the Sun must therefore be deficient in brightness at the corresponding limbs. Even after the lenses had been secured, the demands of other phases of the Observatory's work greatly retarded the construction of the instrument, and it was not until the latter part of 1899 that it was ready for trial.

THE RUMFORD SPECTROHELIOGRAPH[3]

The design finally adopted was reached only after long and careful consideration of the special conditions of the problem. As has already been stated, the ideal form of spectroheliograph is that in which the instrument is moved as a whole, while the image of the Sun and the photographic plate are stationary. It was impossible, however, to use an instrument of this kind with the forty-inch refractor, as the great weight of the moving parts would have thrown the telescope into vibration, thus preventing good images from being obtained. The only feasible solution of the problem seemed to require that the motion of the Sun's image across the first slit be produced by a uniform motion of the telescope tube in right ascension or declination, the photographic plate being moved at the same time across the second slit. The obvious mechanical difficulties of carrying this plan into effect with a telescope sixty-four feet (19.5 m) in length were not overlooked at the time, but it seemed necessary to meet these difficulties and to endeavor to overcome them by the best means at command. The slow-motion electric motors provided by Messrs. Warner & Swasey could evidently be adapted to produce the necessary motion of the solar image and plate. For certain reasons it would have been preferable to move the instrument in right ascension. But the necessity of connecting the photographic plate directly with the slow-motion motor led to the choice of the declination motor, as this is mounted on the tube in such a position that a shaft could be run from it to the lower end of the telescope, while the right-ascension motor is mounted on the declination sleeve, at a considerable distance from the telescope tube. It would therefore be difficult to connect it in any simple way with the screws which drive the plate-carriage.

A photograph of the spectroheliograph is reproduced in Plate I. It will be seen that it consists essentially of a heavy circular iron casting, below which extends a skeleton frame, which supports the collimator and camera tubes and the cast-iron bracket that forms the base of the prism box. When in use on the telescope the instrument is borne by the large ring, supported by four tubes, which is used to carry all of the spectroscopes and other heavy attachments employed with the forty-inch refractor. This ring can be racked in and out along the axis of the telescope, thus permitting the first slit of the spectroheliograph to be set in the focal plane of the forty-inch objective corresponding to light of any desired wave-length.

Slits.—The two slits of the spectroheliograph are each eight inches long, curved as described below. The first slit is of very simple construction, one jaw being fixed, the other movable by a micrometer screw. The jaws are of brass, nickel plated and polished so as to reduce the heating by the Sun, which is very great on account of the large diameter of the image. In the first experiments with the instrument it was found that as the Sun moved slowly across the slit the heating of the jaws caused them to come together along the central part of the slit, thus cutting off the light from parts of the plate during the exposure. This difficulty was remedied by mounting a light metallic screen, pierced by a long narrow window, a short distance in front of the slit.

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[3] This name has been adopted in recognition of the grant of the Rumford Committee

During the long exposures required in photographing the chromosphere and prominences at the limb, it is desirable to exclude the direct light of the Sun's disk from the collimator. With such an instrument as the Kenwood spectroheliograph, where the image of the Sun is fixed with reference to the collimator, this can be done very simply by means of a metallic disk, slightly smaller in diameter than the Sun's image, supported directly in front of the slit. In the Rumford spectroheliograph, however, the Sun's image moves across the slit during the exposure. For this reason the occulting disk must be moved during the exposure at the same rate as the Sun's image. This is accomplished by mounting the disk on a light carriage, which moves a little above the first slit. The motion of this carriage is produced by a rod connecting it with the plate-carriage, which moves behind the second slit and contains the photographic plate. The length of the arm connecting the two carriages can be varied by means of a rack and pinion, thus permitting the Sun's image to be kept central on the disk, even if there is some drift of the image (due to imperfect adjustment of the driving-clock) during a long exposure.

The second slit is similar to the first slit, but additional adjustments are provided. As in the case of the first slit, one jaw is fixed, while the other is opened by means of a micrometer screw, so extended that its divided head projects from the end of the light-tight box in which the plate-carriage slides. A second screw, also provided with a graduated head, permits the second slit as a whole to be moved parallel to itself. This greatly facilitates the setting on the spectral lines, which is accomplished in the manner described below.

Both the first and the second slits are provided with means of rotation in their own plane. These permit the first slit to be made parallel to the refracting edge of the prisms, and the second slit to be made parallel to the spectral lines. The latter adjustment must be made with great accuracy, on account of the considerable length (8 inches = 20.3 cm) of the slit and the spectral lines. The difficulty is increased by the fact that the box containing the plate-carriage and the second slit must be removed from the spectroheliograph whenever this instrument is detached from the telescope. When replaced on the spectroheliograph, the box is rotated until a projecting arm comes in contact with a strong adjustable stop. In practice little difficulty is experienced in securing and retaining the necessary parallelism of the slit and the lines.

In a spectroheliograph of this size the curvature of the slits necessarily plays an important part. It is obvious that if the first slit were straight and the second slit were given the necessary curvature (twice that of the lines in Fig. 1, Plate II) the image of the Sun would be greatly distorted, flattened on one side and drawn out on the other. In the present instrument a method of overcoming this difficulty, suggested several years ago by Professor Wadsworth,[4] was adopted. The curvature was equally divided between the first and second slits, and the direction of the motion of the photographic plate was made the same as that of the Sun's image. A little consideration will show, when the optical train of the instrument is taken into consideration, that this plan will eliminate the distortion of the image which would be expected to result from the use of curved slits. It is only necessary that the collimator and camera lenses be of the same focal length, and that the speed of the solar image and plate be equal, in order that circular and undistorted photographic images may be obtained. When the curved first slit is used the curvature of the lines corresponds with that shown in Fig. 1, Plate II, which is a full-size reproduction of a photograph of the solar spectrum taken with the second slit removed.

Optical parts.—The collimator and camera lenses are of the portrait-lens type, by Voigtländer. They are of equal aperture and focal length and may be focussed singly or together by means of a rod connecting the pinions which move each lens in its tube. The collimator and camera tubes are provided with a large number of diaphragms, which effectually prevent reflection of light from the inside of the tubes, a point of great importance in the design of spectroheliographs.

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[4] W. H. WRIGHT, *Astrophysical Journal*, Vol. V (1899), p. 325.

After passing through the collimator lens the rays meet a plane mirror. From this they are reflected to the first of two prisms which, in conjunction with the mirror, give a total deviation of 180° when the prisms are at minimum deviation for the line in use (Fig. 1). As ordinarily employed, the mirror and prisms are clamped in position for the K line. But if it is desired to pass to another part of the spectrum, the prisms are first set at minimum deviation for the desired wave-length, the setting being made with the aid of a pointer moving over a scale on the lower face of the prism box. The mirror is then moved along the axis of the collimator until a position is reached in which light of the desired wave-length, when reflected from the center of the mirror, will pass centrally through the prisms at minimum deviation. The position of the mirror is read off on a scale on the top of the prism box (Fig. 1 is from a photograph taken with the top of the box removed). The mirror is rotated by means of a tangent screw, controlled by the observer at the second slit by a rod passing up through the frame of the spectroheliograph (Plate I). The tangent screw and the top of the prism box can be removed in a moment, thus giving easy access to the interior. Diaphragms within the prism box prevent diffuse and reflected light from reaching the camera lens.

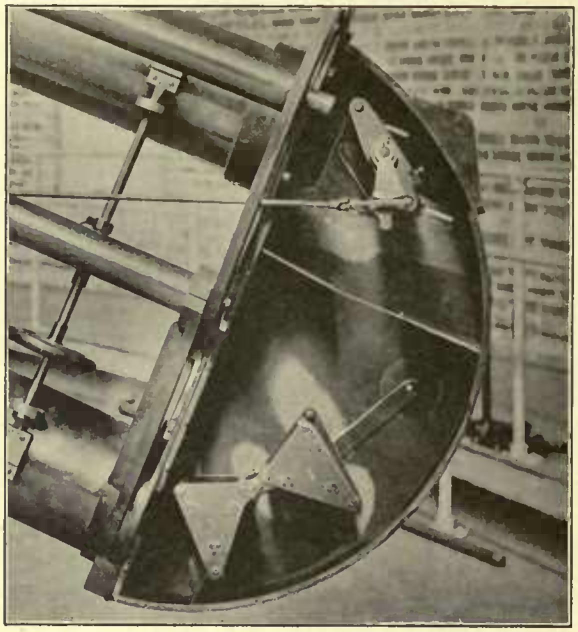
FIG. 1.—Prism-Box

The relative position of mirror and prisms is of importance, and in this respect the present spectroheliograph is a distinct improvement upon the instrument used in my experiments on Mount Etna. In the case of that instrument the mirror (there in the form of a reflecting prism) stood in front of the camera lens, whereas in the present instrument the mirror is placed in front of the collimator lens. With this latter arrangement the diffuse light from the mirror is dispersed and thus greatly reduced in intensity by its passage through the two prisms.

In this connection it may be remarked that one of the most important elements of spectroheliograph design is the question of diffuse and reflected light. Too much care cannot be taken to eliminate it, both by devices such as have been suggested in the case of the mirror, and by a thorough use of diaphragms and other similar means of protection. A thorough study of this question has been made with several spectroheliographs employed with the forty-inch refractor. During the test of the Rumford spectroheliograph two other spectroheliographs of different design were available for comparison with it. The moving slits, which had been removed from the Kenwood spectroheliograph, were replaced, permitting it to be employed for photographing small areas of the large solar image. A spectroheliograph of the Littrow form suggested by Newall[5] was also constructed. But, in spite of every precaution to eliminate diffuse and reflected light, including modifications of Mr. Newall's design so as to place the first and second slits at a considerable distance from the principal axis of the instrument; the insertion of a very complete system of diaphragms; and the use of a screen covering the central part of the joint collimator and camera lens (for the purpose of preventing light due to internal reflections from reaching the second slit)—so much scattered light remained that the photographs did not show satisfactory contrast. The Kenwood spectroheliograph was also deficient in this respect, as the illuminated face of the grating (or that of the 30° reflecting prism sometimes employed in its stead) could be seen directly from the second slit.

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[5] *Proc. Cambridge Phil. Soc.*, Vol. IX (1896), p. 179.

In the Rumford spectroheliograph, as has been remarked, these difficulties do not exist, and the resulting photographs clearly show the advantages of this instrument, either for work with two prisms and a mirror, or for that demanding the higher dispersion obtained when a grating is substituted for the mirror.

The question of the best dispersion for a spectroheliograph is one which has been considerably discussed, notably by Michelson.[6] As shown in his paper, the contrast should increase with the resolving power up to a certain point, defined by several conditions, the principal of which is the width of the spectral line employed. In the case of the calcium flocculi, a comparatively small resolving power is sufficient to give the best results. On the whole, it is probable that no important advantage will be gained in this case by increasing the resolving power above that of two 60° prisms (assuming the effective linear aperture of the spectroheliograph in the plane of dispersion to be as great as 5 cm). As compared with gratings, prisms possess certain advantages, though they are not free from disadvantages. In general they have the decided advantage of giving a brighter spectrum, in which the H and K lines are visible, and the diffuse light is also less than with most gratings. On the other hand, the curvature of the spectral lines is much more marked than with gratings, and this circumstance seriously affects the design of the spectroheliograph. On the whole, prisms are usually to be preferred to gratings.

The need of high dispersion is most manifest when the dark lines of the solar spectrum (with the exception of the broad H and K bands) are to be employed in photographing the Sun's disk. As these lines are dark only by contrast, it is of course possible to obtain monochromatic images corresponding to them with the spectroheliograph. But in order that these images may represent the gas or vapor which gives rise to the line, it is absolutely essential that the dispersion be great enough to make the line wider than the second slit, in order that no light from the continuous spectrum on either side of the dark line may fall upon the plate. Misleading results will be obtained unless this condition is fulfilled. In this case, therefore, the dispersion of one or two prisms will not suffice, unless a camera much longer than that of the Rumford spectroheliograph be used. The necessary increase of dispersion is obtained in a very simple manner in the Rumford spectroheliograph. A large plane grating, having the usual adjustments, is mounted on a support which can be substituted in a moment for the support of the mirror in the prism box. The grating employed has 20,000 lines to the inch (7874 to the cm) on a ruled surface $2\frac{5}{8}\times3\frac{3}{4}$ inches (66×95 mm). Any line in the first-order spectrum can be made to fall on the center of the first prism, whence it is transmitted at minimum deviation through the two prisms of the train. This adds the dispersion of the grating to that of the prisms, and has the additional advantage of reducing the diffuse light of the grating to a minimum. With the grating at present employed the lines of the ruled surface are not long enough to permit the entire length of the first slit to be used: a zone of the solar disk only about 2.5 inches (6.4 cm) wide can be photographed in this way. The dispersion is sufficient to enable photographs to be taken through such lines as those of hydrogen, λ 4226.9 (*Ca*), λ 4383.7 (*Fe*), and a few other of the more intense lines. In order to use narrower lines, still higher dispersion, which is now being provided for in another spectroheliograph, will be required.

In the case of the prominences, the high dispersion of a grating or of several prisms is frequently advantageous (except in eruptions, where the lines are distorted through motion in the line of sight), since the H and K lines are narrower in the prominences than in the flocculi, and are therefore less widened by dispersion; hence high dispersion increases the contrast by decreasing the relative brightness of the sky spectrum. This advantage is nevertheless partly offset by the disadvantage arising from the longer exposure required when high dispersion is used.

Motion of solar image and plate.—In their original design of the mounting for the forty-inch refractor Messrs. Warner & Swasey provided electric motors for the slow motions in right ascension

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[6] *Astrophysical Journal*, Vol. I (1895), p. 1.

and declination. These have proved exceedingly useful, especially in work with the stellar spectrograph, where they are employed to keep the star accurately centered on the slit throughout the exposure. In order to adapt the declination motor for the purposes of the spectroheliograph, it was provided with two sets of change gears, designed by Mr. Ritchey and constructed in the instrument shop of the Observatory. The motion of the focal image of the Sun produced by the motor when these gears are employed is about one minute of arc in four seconds and twenty-four seconds of time respectively. The motion of the telescope when driven by the motor was thoroughly tested, before the spectroheliograph was designed, by photographing the trails of bright stars. It was found to be steady and uniform, the slight jarring of the tube caused by the motor producing no apparent effect upon the photographs.

The motion of the photographic plate behind the second slit, which must correspond exactly with the motion of the solar image over the first slit, is produced by a shaft extending down the telescope tube from the declination motor, to which it is connected by suitable gearing. This shaft runs in ball bearings, and with the two speeds of the motor makes one revolution in seven-tenths of a second and in four seconds respectively. Various means of driving the photographic plate through the motion of this shaft have been employed. These include a double Hooke's joint;[7] a worm gear mounted on a bracket on the spectroheliograph ring at the lower end of the shaft, which drove a drum on which was wound a steel tape connected directly with the plate-carriage; and a grooved pulley connected by a round leather belt with a pulley at the end of the light-tight box in which the plate-carriage moves. This last arrangement is the one now employed. The motion of the carriage is produced by means of two screws, each of one millimeter pitch, which run longitudinally through the box containing the carriage, and are connected with the carriage by means of split-nuts which can be opened and closed by keys on the outside of the box. The pulley on which the leather belt runs is attached to a spur gear, which engages with two other spur gears of equal diameter on the projecting ends of the screw shafts. As the two grooved pulleys are nearly equal in size, the number of revolutions of the screws corresponds closely with the number of revolutions of the shaft on the telescope tube. The exact adjustment of the speed of the plate to that of the solar image is secured by giving these pulleys the proper relative diameters. The circularity of the solar image on the photograph gives an accurate means of testing this adjustment.

From the outset serious difficulty has been experienced in producing an absolutely uniform motion of the plate, which would result in a photograph free from lines or regions of varying density parallel to the slit. These difficulties greatly retarded the completion of the instrument, and though almost wholly eliminated at the present time, lines about one millimeter (or less) apart sometimes appear on the photographs taken with the telescope in certain positions. The end-thrust bearings of the screws have been found to be the most sensitive factor in the production of these lines. Many changes have been made in the screw and its bearings, the nuts and their supports, the plate-carriage and the wheels on which it rolls, etc. The recent substitution of two screws for the single screw formerly employed to drive the carriage has almost wholly eliminated the lines. When the seeing is good and the plates show fine detail, they are usually barely visible or altogether absent, but poor definition renders them more conspicuous. Care must be taken to discriminate between appearances sometimes produced by these lines and those which are of truly solar origin.

The carriage is mounted on ball-bearing wheels running on V-shaped tracks. The plate-holder is placed in the carriage through a door at one end of the light-tight camera box. When thus inserted it is held against the back of the carriage by springs. After closing the door, which forms a light-tight contact with the cloth-covered end of the plate-holder when the carriage is at the end of the box, a small sliding door is opened. Through this the slide in front of the plate can be withdrawn without admitting light to the box. After the sliding door is closed, the carriage is

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[7] Shown in a photograph of the spectroheliograph reproduced in the *Astrophysical Journal*, Vol. XVI (1902), Plate VII.

moved a short distance forward on the tracks, and the plate-holder is pushed down in the carriage by two screws, turned by screw drivers which project through the back of the camera box. This brings the film of the photographic plate almost in contact with the jaws of the second slit, which we may suppose to be set on the K line. The split-nuts are then clamped to the driving screws and the motor started. The Sun's image then moves across the first slit, while the photographic plate moves at the same rate across the second slit. At the end of the exposure the split-nuts are unclamped and the plate-carriage moved back to the point where the screws which hold the plate forward in the carriage may be released. After releasing the screws the plate-carriage is moved to the end of its run, the sliding door opened, and the slide inserted in the plate-holder. The hinged door may then be opened, and the plate-holder removed from the carriage.

Method of setting the second slit on a line.—An important element in the design of any spectroheliograph is the means provided for setting the second slit upon any desired line in the spectrum. In the numerous forms of spectroheliographs which I have designed, various methods of accomplishing this have been employed. Two methods, the choice of which depends upon the character of the line selected, are used in the Rumford spectroheliograph. A compound microscope, of variable magnifying power, is mounted opposite the second slit on the camera box. This microscope is supported on a strip of metal running in guides, which permit it to be displaced in a direction at right angles to the second slit. The microscope is focused on the lines of the spectrum when seen through the widely-opened slit. Under these conditions the jaws of the second slit will be sufficiently well in focus, as the focal plane, corresponding with the position of the film when the plate is pushed forward, almost coincides with the plane of the slit jaws. The mirror or grating is rotated by means of the tangent screw until the desired line enters the field of view. A single thread, in the filar micrometer of the microscope, is brought into accurate coincidence with the spectral line by means of the micrometer screw. The second slit is then closed to the desired width, and moved as a whole until it coincides with the micrometer thread. Under these circumstances it must coincide with the line on which this thread has previously been set.

When using the K line it is usually more satisfactory, on account of the faintness of the spectrum and the loss of light in the microscope, to bring the line into position on the slit with the aid of a simple hand magnifier. H is more easily seen than K, and since it gives equally good results with the Rumford spectroheliograph, it is now regularly employed.[8]

As the H and K lines are nearly at the extreme limit of vision, it is sometimes advantageous to make the first slit tangential to the solar image, where the bright reversal of the line may be seen. This may be set upon more accurately than the broad dark shade. The use of a fluorescent eyepiece might facilitate setting on the H and K lines. The expedient of setting on a line by the aid of the overlapping spectrum may sometimes prove useful when a grating is used without prisms. In the Rumford spectroheliograph this method is not available, since a grating is used only in conjunction with prisms, which effectually eliminate the overlapping spectra.

When it is desired to photograph the calcium vapor at different levels in the flocculi, the method described on p. 16 must be employed. This requires that the second slit be set at various points on the broad H or K bands, at known distances from the center. If we assume that the first photograph of a series corresponding to different levels is made with the second slit set at the center of the H band, successive photographs may be obtained, without removing the plate-holder from the carriage, by moving the second slit as a whole through any desired number of divisions of the micrometer head of the screw connected with it. This method is much more rapid than repeated settings with the microscope would be, thus permitting various stages of a rapidly changing disturbance to be photographed.

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[8] Since K is brighter than H, it would usually be preferred with telescopes which absorb less light of this wave-length. The flocculi seem to have the same form in images obtained with either of these lines.

For work in the ultra-violet, where the lines cannot be directly observed, the expedient may be employed of photographing the spectrum and measuring the distance on the plate from a known line in the visible spectrum to the desired line in the ultra-violet. An auxiliary microscope, provided with a right-angle prism, and projecting through the side of the camera tube so as to receive light from the spectrum on one side of the second slit, may then be placed at a position corresponding to this measured distance, and the setting effected by bringing the visible line into coincidence with a thread in the eyepiece of this microscope. If the distance is not too great, the same thing can be accomplished by observing the visible line through a small door in the brass plate which carries the second slit.

Photographs may be made simultaneously in two or more lines, if certain conditions be fulfilled. The most important requirement is that the solar image shall be in focus on the first slit for each of the wave-lengths in question. Except in the case of two lines symmetrically placed on opposite sides of the point of inflection of the color curve of the telescope objective, this condition cannot be fulfilled with an instrument like the forty-inch Yerkes refractor, where the color curve is very steep in the blue and violet. For this reason no experiments in this direction have as yet been attempted with the Rumford spectroheliograph. With the new Snow horizontal telescope the exclusive use of mirrors should eliminate the difficulty arising from chromatic aberration, and render such work feasible.

Adjustments.—The adjustments of the Rumford spectroheliograph are made as follows:

1. Square up the prisms on their leveling screws by observing reflections from the three faces.
2. Square up the mirror by observing the image of a fine wire fastened across the center of the first slit.
3. Focus the collimator by observing the image of a wire returned to the plane of the slit by the mirror standing normal to the axis.
4. Determine the position of minimum deviation of the prisms for the H line.
5. Focus the camera by photographing the solar or sky spectrum in the H region.
6. Determine the magnification parallel to the slit by placing wires across the first slit, photographing the spectrum, and comparing the distances between lines on the photographs with the distances between the wires themselves.
7. Check the adjustment of the mirror by placing a wire across the center of the first slit and noting whether the image falls at the center of the second slit.
8. Make the first slit perpendicular to the direction of dispersion by placing a wire across the center, photographing the spectrum with the slit at various position angles, and measuring the plates to find whether the central line is perpendicular to a tangent at the center of the curved spectral lines.
9. Readjust the prisms for minimum deviation of H, using an electric arc containing calcium, and repeat (6), after refocusing by Newall's method.
10. Make the second slit parallel to the spectral lines by observing them at the ends and center.
11. To determine whether the motion of the plate is parallel to the direction of dispersion: Make a series of photographs of the spectrum with wide second slit, moving the carriage between exposures. Determine by measurement whether the dust lines are perpendicular to a tangent at the center of the spectral lines.
12. To set the first slit at right angles to the motion of the forty-inch telescope in declination: Draw on a plate in the visual focus a line perpendicular to the curved slit at its central point. Set the telescope on the Sun, and rotate the spectroheliograph in position angle until the Sun's limb exactly follows this line when the telescope is moved in declination by the motor.
13. Adjust the speed of the plate-carriage until the diameters of the solar image, as measured in different position angles, are equal.

Before making the above adjustments it is assumed that the first and second slits have been given the proper curvature for eliminating distortion of the image. This is done by photographing the H line through the widely opened second slit, using a straight first slit. The curvature of the H line is then determined by measurement of the photograph, and the first and second slits are made of twice this radius of curvature.

PRELIMINARY ACCOUNT OF RESULTS OBTAINED WITH THE RUMFORD SPECTROHELIOGRAPH

Although the present paper is intended mainly as a description of the Rumford spectroheliograph, it seems desirable that it should be accompanied by some recent photographs of solar phenomena, since in this way the uses of the spectroheliograph for various classes of work can be most easily made clear. The publication of the photographs, however, necessarily involves some preliminary remarks on the working hypothesis which has been employed to interpret them. The hypothesis is used mainly as a guide to further research; for, while it seems to describe in a fairly satisfactory manner many of the phenomena photographed, it is of course open to modification or rejection in the light of future results.

Prior to 1903 the spectroheliograph was used for experimental purposes, the numerous photographs obtained during the Sun-spot minimum being of service mainly in perfecting the adjustments of the instrument. It had been expected that the spectroheliograph would be transferred from the forty-inch refractor to the thirty-inch cœlostat reflector for the purposes of the daily record; but the destruction of the latter instrument by fire in December, 1902, prevented the realization of this plan.[9] The work with the forty-inch refractor was accordingly resumed in February, 1903, and since the latter part of that month photographs of the calcium flocculi have been made on each clear day (Sundays usually excepted). Since early in April this series has been supplemented by a daily series of (low-level) photographs, made with the slit set at some distance from the center of the H or K band, and since May 16 photographs have been made as often as possible with the $H\beta$ line. In addition to this routine work, many photographs of special regions have been taken in a study of the calcium vapor at various levels, and some results have also been obtained with the calcium line λ 4226.9, the iron line λ 4383.7, and with various other dark lines. It will thus be seen that while the material represented by the photographs obtained with the Rumford spectroheliograph is not yet sufficient for extended generalizations, the variety of phenomena recorded is such as to call for some comment here. A more complete discussion of the results must be reserved for a future occasion.

ON THE NATURE OF THE CALCIUM FLOCCULI

In my first published note on the bright calcium regions recorded for the first time with the Kenwood spectroheliograph, I briefly described the results in the following words:

> The reversed regions are of great extent, and in appearance closely resemble faculæ. Several explanations may be suggested to account for them. They may be:
>
> 1. Ordinary prominences projected on the disk.
> 2. Prominences in which H and K are bright, while the hydrogen lines are absent.
> 3. Faculæ.
> 4. Phenomena of a new class, similar to faculæ, but showing H and K bright, and not obtained in eye observations or ordinary photographs because of the brilliant background upon which they are projected.[10]

It was subsequently shown that the bright calcium regions in general coincide closely with the faculæ, and it was concluded that they represent the hot calcium vapor in the upper part of the faculæ and in the lower part of the adjoining chromosphere. Fig. 2, Plate II, which is reproduced from a photograph of the K line taken at the Kenwood Observatory, shows that the bright reversals of the K line frequently occur in regions of the disk where the continuous spectrum is considerably strengthened. These regions are the faculæ proper. The faculæ, though apparently but little brighter than the photosphere, are conspicuously visible near the Sun's limb. This is probably due to the fact that they reach a higher level, and thus escape much of the general absorption exercised by a comparatively thin stratum of a smoke-like nature, which lies in close contact with the photosphere. The faculæ are, in general, the regions above which the calcium vapor is hottest and most brilliant. But it appeared later that the calcium vapor is not confined to the faculæ, but extends beyond their boundaries and

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[9] Through the generosity of Miss Helen Snow, the cœlostat reflector has been rebuilt, and is now in regular use. A spectroheliograph will soon be employed with it.

[10] *Astronomy and Astrophysics*, Vol. II (1892), p. 159.

frequently occurs in regions of the solar disk where they are absent. The generally close coincidence of the calcium clouds with the faculæ, and a natural hesitation to propose a new name before the results obtained with the spectroheliograph had been sufficiently studied, led me to apply this term to the bright calcium regions photographed with the spectroheliograph. From my present point of view I think it would have tended to clearness, as M. Deslandres has pointed out, if some other name had been adopted.

M. Deslandres' latest explanation of the calcium regions is undoubtedly more nearly correct than my earlier one, though at the time I did not appreciate this. His solar investigations at the Paris Observatory were confined for some years to the photography of the spectrum of various parts of the Sun's disk, but in 1894 he undertook work with the spectroheliograph. The bright reversals of the H and K lines photographed by M. Deslandres on the Sun's disk were at first considered by him to represent the prominences; later he ascribed them to bright regions at the base of the prominences, and finally he spoke of them as the brighter regions at the base of the chromosphere projected on the disk. This last designation now appears to me to describe the facts much more accurately than the term "faculæ" (meaning calcium vapor of the faculæ) at first employed by myself. In suggesting the term *flocculi* (*flocculus*, dim. of *floccus*, "a bit of wool"), to distinguish the vaporous clouds photographed on the disk from the underlying faculæ, I have distinctly avoided the use of a name which might in any sense be taken as indicating the nature of the phenomena. A glance at Plate III will show that the word is more or less descriptive of the photographs, so far as their appearance is concerned.[11] It is necessary to speak of calcium flocculi, hydrogen flocculi, etc., as the photographs show that the forms of the various vapors in the same part of the disk are not identical. Some of the phenomena comprised under this name are undoubtedly prominences seen in projection, but most of them correspond to much lower levels, near the base of the chromosphere, or within the reversing layer.

MINUTE STRUCTURE OF THE FLOCCULI

The extensive literature which embodies the long discussion regarding the "willow leaf" and "rice grain" structure of the photosphere has in large part become obsolete since the publication of Langley's important paper "On the Minute Structure of the Solar Photosphere," and of Janssen's excellent photographs, now generally accessible in the first volume of the Annals of the Observatory of Meudon. After speaking of the cloud-like character of the photosphere, Langley goes on to describe the more minute details in the following words:[12]

> Under high powers used in favorable moments, the surface of any one of the fleecy patches is resolved into a congeries of small, intensely bright bodies, irregularly distributed, which seem to be suspended in a comparatively dark medium, and whose definiteness of size and outline, although not absolute, is yet striking by contrast with the vagueness of the cloud-forms seen before, and which we now perceive to be due to their aggregation. The "dots" seen before are considerable openings caused by the *absence* of the white nodules at certain points, and the consequent exposure of the gray medium which forms the general background. These openings have been called pores; their variety of size makes any measurements nearly valueless, though we may estimate in a very rough way the diameter of the more conspicuous at from 2″ to 4″. The bright nodules are themselves not uniformly bright (some being notably more brilliant than their fellows and even unequally bright in portions of the same nodule), neither are they uniform in shape. They have just been spoken of as relatively definite in outline, but this outline is commonly found to be irregular on minute study, while it yet affects, as a whole, an elongated or oval contour. Mr. Stone has called them rice-grains, a term only descriptive of their appearance with an aperture of three to four inches, but which I will use provisionally. It depicts their whiteness, their relative individuality, and their approximate form, but not their irregular outline, nor a certain tendency to foliate structure which is characteristic of them, and which has not been sufficiently remarked upon. This irregularity and diversity of outline have been already observed by Mr. Huggins. Estimates of the main size of these bodies vary very widely. Probably Mr. Huggins has taken a judicious mean in averaging their longer diameter at 1″.5, and their shorter at 1″, while remarking that they are occasionally between 2″ and 3″, and sometimes less than 1″, in length.

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[11] The name was suggested by my friend Dr. L. F. Barker, after seeing the photographs.

[12] *American Journal of Science*, Vol. VII (February, 1874).

> . . . . In moments of rarest definition I have resolved these "rice-grains" into minuter components, sensibly round, which are seen singly as points of light, and whose aggregation produces the "rice-grain" structure. These minutest bodies, which I will call granules, it will appear subsequently can hardly equal 0″.3 in diameter, and are probably less.
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> . . . . It seems to me that there is no room for doubt that "filaments" and "granules" are names for different aspects of the same thing; that filaments in reality are floating vertically all over the Sun, their upper extremities appearing at the surface as granules; and that in the spots we only see the general structure of the photosphere, as if in section, owing to the filaments being here inclined.
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> . . . . Speaking without reference to spectroscopic investigations, it seems to me that we have in the behavior of our filaments a presumption as to the existence of ascending currents in the outer penumbra, and of both ascending and descending currents at the umbral edge; ascending ones being the more usual.

An examination of the minute calcium flocculi photographed with the Rumford spectroheliograph will show that they closely resemble the photospheric "grains" described by Langley and illustrated in Janssen's photographs. Fig. 3, Plate IV, is reproduced from one of our negatives on the scale chosen for the majority of the photographs in Vol. I of the Meudon Annals. This photograph was made with the slit set at the center of the H line on a day when the seeing was particularly good. In Fig. 5, Plate II, squares 10 seconds of arc on a side are shown. These permit of an accurate determination of the size of the individual elements of the structure. Measurements made on our best negatives show that the minute calcium flocculi range in diameter from less than one second to several seconds of arc, thus corresponding closely with the "grains" of the photosphere.

On the working hypothesis at present employed to interpret the results obtained with the Rumford spectroheliograph, it is considered that these minute flocculi are columns of calcium vapor, rising above the columns of condensed vapors of which the photospheric "grains" are the summits.

On such an assumption it becomes interesting to inquire whether the larger calcium flocculi are made up of similar columns of calcium vapor. As a rule, the seeing is hardly good enough to permit a decision to be reached on this point. But under the best conditions there appears to be distinct evidence of a filamentary structure, the filaments seeming to spread out like the branches of a tree (Fig. 2, Plate IV). It is evident that much light could be thrown on the question if it were possible to photograph sections of the flocculi at different elevations above the photosphere, since in this way the form and size of distinct columns of calcium vapor, if such were present, could be determined at different levels.

FORM AND EXTENT OF CALCIUM FLOCCULI AT VARIOUS ELEVATIONS ABOVE THE PHOTOSPHERE

Fortunately, it is possible to accomplish this very result, if the present mode of explaining the photographs may be regarded as sound. We have already had occasion to consider some of the characteristics of the H and K reversals in the chromosphere. In the solar spectrum itself the appearance of the H and K lines clearly indicates that calcium vapor occurs under widely different conditions of intensity at various levels above the photosphere. It is a well-known fact that if a considerable quantity of calcium vapor is introduced into an electric arc, broad bands, bright in the center and fading toward both edges, will appear at the position of the H and K lines (Fig. 4, Plate II).[13] The width of the bands may be taken as an approximate measure of the density of the calcium vapor, which decreases toward the outer part of the arc, where the bands are reduced to narrow lines. The narrow dark lines at the center of the bright bands are caused by the absorption of the comparatively cool and rare calcium vapor in the outer part of the arc.

A similar condition of things undoubtedly exists in the Sun. In the first place, we have broad diffuse dark bands in the solar spectrum at H and K, produced by comparatively dense calcium vapor close to the photosphere. For convenience of reference these bands will be called H_1 and K_1. As the bright reversals at the base of the chromosphere, when photographed at the Sun's limb with a

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[13] Photographed in the electric arc with the solar spectrograph of the Snow horizontal telescope. The grating temporarily employed gives strong ghosts, which are conspicuous in the photograph.

tangential slit, or at a total eclipse, are much narrower than these bands, it may be concluded that the dense calcium vapor in the chromosphere lies beneath the lowest level that can be observed at the limb. On the basis of Kirchhoff's law, the comparative darkness of these bands in the solar spectrum would be ascribed to the fact that the calcium vapor which they represent is cooler than the photosphere below it. With increasing elevation, in a region of lower pressure, the density of the vapor decreases, and to this decrease of density there corresponds a decrease in the width of the bands. In the lowest portion of the chromosphere that can be observed at the Sun's limb, the density of the vapor is so far reduced that the broad and diffuse bands are replaced by fairly well-defined lines (H_2, K_2), which maintain their width up to a certain elevation in the chromosphere and then grow narrower, thinning out to much narrower lines (H_3, K_3) in the upper chromosphere and prominences (Fig. 3, Plate II). On the disk H_3 and K_3 appear as fairly narrow dark lines at the center of the broad H_1 and K_1 bands. They occur in practically all parts of the disk, but differ greatly in intensity in different regions. Every bright calcium flocculus on the disk is characterized by the presence of bright H_2 and K_2 lines at the center of H_1 and K_1, with narrow dark H_3 and K_3 lines, due to the absorption of the cooler and rarer vapor in the upper chromosphere, superposed upon them. Intensity curves showing these peculiarities of the H and K lines are given by Jewell in the *Astrophysical Journal*, Vol. III (1896), p. 100, where the displacements of the lines are also discussed. They are also illustrated in the photographs reproduced in Plate II.

From a strict application of Kirchhoff's law it would appear that the calcium vapor in the lower chromosphere is actually hotter than the calcium vapor which lies above and below it. It seems improbable that the law can be rigorously applied in this case, and hence it may be necessary to attribute the strong radiation of the intermediate layer to causes other than temperature alone.

In view of the composite character of the calcium lines, it should be possible with the spectroheliograph to photograph sections of the calcium flocculi at levels corresponding to their several elements.[14] If, for example, the second slit were set at the extreme edge of K_1, the resulting photograph should show only that calcium vapor which is dense enough to produce a line of this breadth; *i. e.*, a section across the base of the calcium flocculus should be obtained. Under no circumstances could the upper and rarer portions of the flocculus be shown on such a photograph, since the line they produce is not broad enough to enter the second slit. If the slit were set nearer to the center of the line, the photograph should represent a section of the flocculus corresponding to a higher level, where a narrower line is produced. It is evident that while none of the higher and rarer calcium vapor could be shown in this photograph, it might nevertheless include regions lying below it, where the calcium vapor is dense enough to produce a broader line. However, since the calcium vapor is rising from a region of high pressure to one of a much lower pressure, it must expand as it rises, and therefore a section at any level should in general be of a larger area than a section of the same flocculus at any lower level. As a consequence of the increasing extent of the vapor with the altitude, and the increase of brightness observed when passing from K_1 to K_2, a photograph corresponding to a given level is not necessarily affected in any considerable degree by the existence of the denser vapor below, except in cases where the high-level vapor does not lie immediately above the low-level vapor. Low-level phenomena, even when very bright, may be wholly concealed by general excess of radiation, or in some cases by absorption, of the calcium-vapor at high levels. Moreover, it is of course to be understood that the term "level" is not used here in a strict sense. A section of a large flocculus photographed with K_2 might, for example, correspond to a much greater height above the photosphere than that of the minute flocculi shown on the same photograph. It must never be forgotten, when examining the photographs, that composite effects are very likely to be present.

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[14] Experiments of this kind were not undertaken with the Kenwood spectroheliograph, since the instrument was not well adapted for work with dark lines. Some of the photographs, however, apparently show low-level (K_1) phenomena, and Mr. Evershed informs me that his plates do likewise. M. Deslandres made photographs with K_1 and K_2 in 1894, but I have seen no statements of conclusions derived from a study of the K_1 plates, and do not know whether the method has since been employed at Meudon.

Such considerations regarding the possibility of photographing sections of the flocculi at different levels are borne out by the photographs, as will be seen by reference to the accompanying illustrations. Plate V represents the spot group of 1903, April 29, as photographed with four different settings of the second slit. These were taken within such time limits and in such an order that, as no distinctly eruptive phenomena were present, the principal differences between the photographs are therefore to be attributed to differences in the extent and brightness of the vapor at various levels, and not to changes going on in the Sun at the time.

Fig. 1 shows the various spots of the group, with faint indications of the surrounding faculæ. This photograph was obtained with the slit set on the continuous spectrum at λ 3924, and the form of the faculæ proper, as defined by variations in the brightness of the continuous spectrum, is given in this case. Fig. 2 was made with the slit set at λ 3929, just within the edge of the broad K_1 band. By comparing this with Fig. 1 it will be seen that even the lowest calcium vapor sometimes overhangs and partly covers the penumbra of spots, while the outline of this vapor differs materially from that of the faculæ shown in Fig. 1. Fig. 3 is from a photograph made with the slit set at λ 3932, on the broad dark band near the center of K_1. It will be seen that at this level the vapor has expanded very considerably, so that details of some spots clearly visible in Fig. 2 are completely hidden. Fig. 4 is from a photograph obtained when the slit was in such a position and of such width as just to inclose K_2. This photograph should therefore represent a section of the calcium vapor at the level corresponding to the second stratum referred to above. Here the calcium vapor is brighter and much more extensive than in the stratum below, so that a photograph of the entire Sun taken in this way offers a marked contrast to a photograph taken with the second slit set on K_1 at some distance from the center. It has not hitherto been possible to make photographs corresponding simply to K_3, since very high dispersion will be required in order to prevent the second slit from receiving light from the bright line (K_2) on which K_3 lies. Other series of photographs showing similar differences are reproduced in Plates VI and X to XV.

The assumption that these photographs represent sections of the calcium flocculi at different elevations seems to be the simplest and most satisfactory way of explaining the results obtained. Partial reflection of the bright K_2 line at the edges of the second slit would not suffice to account for the results, since in this case the images of the flocculi would be precisely similar in form in all cases, and would merely vary in intensity. Again, it might be held that the faculæ rise above the dense calcium vapor represented by the broad dark bands at H_1 and K_1, and that they would be shown with increasing contrast toward the center of the bands, on account of the protection from the brilliant light of the photosphere which these afford to the plate. Here again, however, the forms corresponding to all positions of the second slit on H_1 and K_1 should be the same, and they should correspond with those of the faculæ. No satisfactory means of explaining the results except on the assumption that they represent different levels has hitherto presented itself. Essentially conclusive evidence in favor of this assumption is afforded by the photographs of the recent great Sun-spot (Plates X to XV).

With the aid of this additional means of research we may return to a consideration of the structure of the flocculi. It has already been remarked (p. 15) that the general surface of the Sun appears to be covered with columns of bright calcium vapor, varying in diameter from less than a second to several seconds of arc, separated by darker spaces, which correspond in appearance to the darker spaces that separate the photospheric "grains." The summits of these columns seem to lie in the second stratum, corresponding to the bright lines H_2 and K_2. The appearance of the disk, when photographed with the slit set on H_2 at λ 3968.6, is shown in Fig. 3, Plate IV. We must endeavor to explain why the appearance of this photograph differs so markedly from that of Fig. 1, Plate IV, where we see no very clear indication of the existence at the H_1 level of the columns of calcium vapor whose summits appear as minute flocculi in the photographs of the second stratum.

In a photograph taken with the slit set at the center of H or K the contrast between adjacent regions of the Sun's surface depends upon several factors, two of which are in some cases closely related, while in others they are apparently independent of each other. These are the intensity of the dark K_3 line, which may be photographed over almost the entire surface of the Sun, and the intensity of the bright K_2 line, which varies greatly in different regions. Suppose the bright K_2 line to be absent. In this case the contrast between different regions would depend, to a considerable degree,[15] upon variations in the absorption of the calcium vapor in the upper and cooler parts of the chromosphere. If the second slit were not much wider than K_3 a particularly cool region, in the chromosphere or in a prominence, might show as a dark structure.

Let us now suppose, as is actually the case in practice, that K_2 appears as a bright line at numerous points on the Sun's disk. In general, being produced under greater pressure in the lower part of the chromosphere, the bright K_2 should be broader than the dark K_3, while the latter line must appear superposed upon K_2 in all cases but one. This exception is the region over the umbra of Sun-spots, where the denser calcium vapor corresponding to K_2 is absent, and the rarer vapor at a higher level gives a *bright* K_3 line (usually not very intense) on the darker background of the spectrum of the umbra.

It is easy to see that such variations in the relative intensities of bright K_2 and dark K_3 as occur in all parts of the disk must result in photographs showing much greater contrast than is obtained in those corresponding to the K_1 level. For in the latter case the second slit, being set at some distance from the center of K, receives no light from K_2 or K_3, and shows only such variations of intensity as are due directly to differences in the radiation of the dense low-level calcium vapor. The evidence afforded by photographs taken at successive levels goes to show that in passing from the lower K_1 region up into the K_2 region, the calcium vapor increases greatly in radiating power. For example, eruptive phenomena which are quite inconspicuous when photographed at the lower K_1 levels, become more and more brilliant as the second slit is moved for successive photographs nearer and nearer to the center of K. What is true of eruptions is also true in large degree of the smaller columns of calcium vapor, which rise from closely set points all over the Sun's surface, and produce the granulated appearance which is so striking in the K_2 photographs.

These considerations would seem to throw some light on the pronounced difference in contrast between K_1 and K_2 photographs of the solar surface. In the brighter flocculi the contrast in the upper K_1 levels is marked, though it almost wholly disappears at the lowest K_1 level. But in the minute flocculi, which probably lie at lower levels than the large flocculi, the brightness at the K_1 level does not appear to be sufficiently great to give strong contrast effects. The marked increase in brightness which is characteristic of K_2, sometimes enhanced by an increase in the strength of the dark K_3 line in adjoining regions, tends greatly to heighten the contrast obtained when the second slit is set so as to include both K_2 and K_3.

In the larger flocculi the surmise of a structure composed of expanding columns of calcium vapor seems to be borne out by the photographs. Compare, for example, Figs. 1 and 2 in Plate IV. At the lower level (Fig. 1) the flocculus is resolved into a series of well-defined elements, of comparatively small area. At the higher level (Fig. 2) the area of the entire flocculus is greatly increased, and there seems to be evidence (hardly visible in the cut) that the columns composing it have arched over, so that they are no longer seen end on. Few photographs are sufficiently well defined to bring out such details, and it cannot be said with certainty that the effects seen at the higher level are always due to separation and bending of the columns, as well as to expansion of each of the individual columns. In any event, the increase in area at this level is sometimes very great, in many cases sufficient to cover not only the penumbra, but also entire spots. Another illustration of the expansion at

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[15] The second slit in the Rumford spectroheliograph is necessarily wider than the average width of K_3; for this reason variations in the intensity of K_1 must also affect the contrast.

increasing altitudes may be seen in the four photographs, corresponding to different levels, which are reproduced in Plate VI. A much finer illustration is afforded by the photographs in Plates X to XV of the recent great Sun-spot.

DARK CALCIUM FLOCCULI

As already remarked (p. 18), the occasional great strength of K_3, especially in regions where K_2 is not present, would lead one to expect that *dark* calcium flocculi might sometimes appear on the photographs. The discovery of dark hydrogen flocculi (p. 20) led us to make a careful examination of our photographs with reference to the possible presence of such objects. In previous work nothing of this kind had been noticed, the darker spaces between bright calcium flocculi having been supposed to represent a general background of calcium vapor, less highly radiating than the flocculi themselves, but exhibiting no such structure as would be expected to appear in case distinct regions, of exceptional absorbing power, were present. Few indications of dark calcium flocculi have indeed been found, but in certain cases there can be no doubt that such phenomena actually exist. One of these cases is illustrated in Fig. 3, Plate VIII. The presence in this region of the Sun of a very dark hydrogen flocculus (Fig. 4) led us to examine the corresponding K_2 photograph. An exceptionally dark structure, corresponding in its general form with the dark hydrogen flocculus, was found in the same position. The two dark regions shown in these photographs resemble each other quite as closely as the dark hydrogen flocculi ordinarily resemble the corresponding bright calcium flocculi.

It is an interesting fact that a K_1 photograph taken at the same time showed no evidence of the presence of this dark region. In other similar cases the same thing has been found to be true. For example, on Fig. 4, Plate V, a dark structure is shown extending upward to the right from a small spot lying a short distance to the southwest of the largest one of the group. In Fig. 3, which corresponds to a lower level, this dark structure is not present, nor can it be seen at the still lower levels represented in Figs. 1 and 2. It will be noticed in Fig. 4 that this dark structure seems to be a part of an extensive dark region which almost completely surrounds the group of calcium flocculi. Similar appearances are found on many of our negatives and may be seen, though not to good advantage, in Figs. 2 and 3, Plate VII, and in Fig. 4, Plate VI. It seems possible that we have here some indications of the cooler K_3 calcium vapor, which rises to a considerably greater height than the K_2 vapor of the bright flocculi, and spreads out so as to cover a much larger region of the Sun's surface. Evidences of similar dark regions may be found in the immediate surroundings of the great Sun-spot, illustrated in Plates XI, XIII, XIV, and XV. These plates also afford several examples of better-defined dark structures superposed upon the bright K_2 flocculi.

From these results it appears, as might be expected, that the dark calcium flocculi are comparatively high-level phenomena, either in the upper part of the chromosphere or in the prominences themselves. It is not yet possible to distinguish with certainty the exact level at which they occur in any given case, but this, and other related questions, can perhaps be solved when it becomes possible to photograph the disk with the K_3 line. There may be some difficulty in making such photographs, since the dispersion must be so high as to exclude completely the brilliant light of K_2 from the second slit. If successful, photographs taken in this way will probably show the calcium prominences as dark regions projected upon the disk.

HYDROGEN FLOCCULI

The method of photographing the Sun with the aid of the dark Fraunhofer lines has already been explained (p. 9). The spectroheliograph is employed exactly as in the case of the bright calcium lines, but the dispersion is increased sufficiently to insure that the width of the dark lines shall be greater than that of the second slit. Under such circumstances photographs corresponding to the hydrogen lines, or to any other dark lines of sufficient width, may be obtained.

The first photograph made with a dark hydrogen line ($H\beta$) was taken with the Rumford spectroheliograph on May 16, 1903. On developing the plate we were surprised to find a structure differing materially from that obtained with H_2 and K_2. Closer examination, and a comparison of the photograph with a K_2 photograph made on the same day, showed that the bright calcium flocculi were replaced on the $H\beta$ photograph by *dark* structures of similar, though by no means identical form. There could be no doubt about the adjustment of the $H\beta$ line on the second slit, since a prominence was shown on the photograph extending above the Sun's limb. At a point near a Sun-spot a brilliant object appeared. The same bright object was found on a high-level K_2 photograph, but it did not appear on a K_1 photograph. This was confirmed by other exposures.

The results given by this first photograph have been borne out in subsequent work. It is found that the hydrogen flocculi are in general dark, though they are sometimes bright in disturbed regions, usually in the neighborhood of Sun-spots. Figs. 1 and 2, Plate VIII, show bright calcium flocculi and the corresponding dark hydrogen flocculi. These are not suitable for an exact comparison of form, since the time interval which separates them is too long to insure the absence of change. Figs. 1 to 4, Plate IX, permit a better comparison to be made, and also show some *bright* hydrogen flocculi (Fig. 2, west of spot). In comparing these photographs three points must be borne in mind. In making the photograph reproduced in Fig. 3, the second slit was not set properly on the $H\beta$ line. For this reason, the true hydrogen flocculi are properly shown only in the central part of the figure. Moreover, this photograph was not as accurately in focus as the others. Finally, in reproducing the photographs the contrast was unduly increased during the photo-engraving process in the case of Figs. 1 and 2, which makes the luminous background appear too bright.

With these points in mind the photographs may be compared. It will be seen that while the outlines of the dark hydrogen flocculi correspond in a general way with those of the bright calcium flocculi, there is nevertheless a marked difference in the characteristic features. The hydrogen flocculi seem to have a definiteness of structure in striking contrast with the formless masses of the calcium flocculi.

One of the first questions that suggest themselves in examining these photographs is with regard to the distance above the photosphere of the hydrogen which produces these dark regions. By comparing the same Sun-spot, as shown in corresponding photographs of the calcium and hydrogen flocculi (Plate VIII), it will be seen that the spot usually appears smaller in the latter case, apparently because the penumbra is more completely covered by hydrogen clouds which radiate more light than the penumbra does. The umbra, on the other hand, appears quite dark in these photographs, from which we may conclude that in this case any bright hydrogen line that may extend over it must be very faint. The phenomena shown in the hydrogen flocculus surrounding the recent great Sun-spot, Fig. 2, Plate XI, seem to illustrate a more complex condition of things. Some of the smaller spots of the group are completely blotted out by the overlying clouds of hydrogen. In certain places brilliant hydrogen flocculi are seen, which usually coincide in position with corresponding bright calcium flocculi. These are doubtless eruptive in character and of comparatively short duration; as already remarked, they are faint or invisible in the very low level calcium photographs. In the case of hydrogen we thus have bright eruptive phenomena, and also, in the immediate neighborhood, the dark masses which usually constitute the hydrogen flocculi. We also find possible indications of bright hydrogen flocculi, not eruptive in character, in the vicinity of Sun-spots (see, for example, Fig. 2, Plate VIII). There seems to be some evidence that the temperature conditions may sometimes change sufficiently to transform a dark hydrogen flocculus into a bright one. Doubtless in some regions the temperature is exactly at the critical point, which would render the flocculus invisible. The whole subject is one which will require much study in the future, and in the present paper it is not our intention to do more than merely to suggest some of the principal characteristics of the phenomena. We have reason to believe, from some photographs obtained when the second slit did not exactly coincide with the center of the $H\beta$ line, that it will be possible to photograph the hydrogen flocculi at low and at high levels, as we have done in the case of the calcium flocculi.

Present indications seem to point to the view that the extensive dark regions photographed when the slit is set at the center of $H\beta$ are hydrogen prominences seen in projection on the Sun's disk. There can at least be no doubt that they frequently occur at points on the disk where large prominences are present. On June 12, for example, a large hydrogen prominence was photographed with $H\beta$ at the east limb of the Sun. Cloudy weather prevented further photographs from being taken until June 15, but on that date an extensive dark region was photographed with the $H\beta$ line at the point on the disk where this prominence should have been carried by the Sun's rotation. It of course does not follow that the dark region was not due to the absorption of the hydrogen in the chromosphere below the prominence. But it seems reasonable to suppose that since the hydrogen gas must cool by expansion in rising to higher levels, the strongest absorption would take place in the prominence, rather than in the chromosphere below. On such a view the more extensive dark hydrogen flocculi would be regarded as quiescent prominences seen in projection, while most of the smaller flocculi might still be due to absorbing masses in the upper part of the chromosphere.

CONCLUDING REMARKS

In his recent important paper on the solar eclipse of May 28, 1900, Mr. Evershed, in attempting to explain the predominance of enhanced lines in the spectrum of the flash, gives the following arguments in favor of his idea that "the spark and arc conditions may *co-exist* at the same altitude above the photosphere":

> It is well known that the outer limit of the chromosphere, as seen in the line α of hydrogen, presents a structure of small filaments like blades of grass covering the entire surface, and very unlike the diffused, indefinite limit which a true atmospheric envelope might be expected to present.
>
> According to Secchi, "at the base of the chromosphere the hydrogen has the shape of small, close filaments which seem to correspond with the granulations of the photosphere."
>
> This structure suggests that the chromosphere is in reality a region of innumerable small eruptions of the same nature as the jets of highly luminous gas which are constantly to be seen with the spectroscope in all regions of the Sun's limb. It is probable, indeed, that these jets, and the larger eruptive prominences, are in reality only the more pronounced manifestations of a phenomenon occurring on a smaller scale everwhere over the solar surface.
>
> The highly heated gases composing these eruptions, which may be supposed to originate below the photospheric level, would lose heat as they ascended by adiabatic expansion and by radiation, and at a certain elevation would precipitate the more refractory substances as highly luminous clouds, forming, in fact, the photospheric granules and the columnar filaments observed in Sun-spots. But the gaseous streams, deprived of their condensable materials, would continue to ascend above the photosphere, finally becoming diffused in the region of the chromosphere. The expanded gases, subsequently subsiding in a relatively cooled condition, would form a strongly absorbing atmosphere settling down uniformly and slowly upon the photosphere, and through which the ascending streams would be forced.
>
> If this really represents roughly the actual state of things, it is clear that the temperature conditions represented by the electric spark and by the arc may both exist at the same altitude above the photosphere, the spark condition in the highly heated ascending gases and the arc condition in the cooler descending gases.[16]

It will be observed that Mr. Evershed's words, written some time before most of the photographs described in the present paper had been obtained, accurately describe some of the phenomena recorded on our plates. Unfortunately, we are not yet able to say whether the minute flocculi are to be regarded as eruptive in character, nor can we state whether the enhanced lines (other than those of calcium) are characteristic of them. It is perhaps worthy of remark, however, that the calcium line λ 4226.7 fails to show a granulated structure at all comparable in appearance with that given by H_2 or K_2. But at present this fact is hardly to be taken as significant, since the technical difficulties of obtaining thoroughly satisfactory photographs through such narrow dark lines are too great to be

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[16] *Phil. Trans.*, Vol. CCI (1903), pp. 471, 472.

wholly overcome with our present apparatus. For the same reason we prefer to base no conclusions at present upon the differences in structure indicated by photographs which we have taken with the H and K and the 4226.9 lines of calcium. The only iron line with which we have hitherto obtained photographs which are at all satisfactory (λ 4383.7) is not an enhanced line, and therefore is not suitable for the purposes of the present inquiry. It is hoped that this and other similar questions may be investigated with the new spectroheliograph which is now being constructed for use with the Snow horizontal telescope.

Another question to which we can only refer in the present paper concerns the motion in the line of sight of the calcium vapor above the solar surface, as related to the form of the calcium flocculi at different levels. A long series of measures of H_2 and K_2, and also of H_3 and K_3, which have been made by Mr. Adams on photographs of the spectrum taken here, indicates that in general the vapor corresponding to the dark H_3 and K_3 lines is ascending, in regions which lie above the bright calcium flocculi. Measures of the two components of H_2 and K_2 are made with greater difficulty, but these also seem to show that the calcium vapor is rising in the flocculi, at a velocity which ordinarily does not differ greatly from about one kilometer per second. Hitherto we have not had an opportunity to investigate the motions in certain special regions of the flocculi, toward which our attention has been directed by some of the phenomena shown in the photographs corresponding to different levels.

In concluding, we may perhaps be permitted to speak of a few of the numerous investigations which can be undertaken by the student of solar physics. If proper use is to be made of the numerous methods of research which are now available, a large number of investigators will be needed, working, if possible, on some co-operative plan, at many stations widely separated in longitude. Even the adequate use of the spectroheliograph alone would be beyond the capacity of any single institution; for, when suitably designed, this instrument will furnish as many photographs of the Sun as there are elements present in its atmosphere, and, in addition to these, many others which represent the peculiarities of certain lines. For example, we have already seen that it will be desirable to ascertain in what degree photographs taken with enhanced lines differ from those taken with other lines of the same element. With a large image of the Sun important results might be expected to follow from a study of photographs of Sun-spots taken with the aid of the widened lines, and with bright lines or other lines which are peculiar to the spot. In view of the constant changes which are going on in the Sun, a few photographs made in any of these ways will not suffice: what is wanted are series continued through at least one Sun-spot period, in order to discover the laws which govern the intensity and the distribution of the various gases and metallic vapors. Furthermore, the great importance of eruptive phenomena, their comparative rarity, and the brief time in which all their phases are exhibited, call for special preparations and methods of work. Spectroheliographs capable of taking several photographs at once through different lines will be essential for any suitable study of eruptive phenomena. If a chain of observatories well distributed in longitude could arrange their work so as to keep the Sun almost constantly under observation, many important eruptions which are now lost would be recorded.

But it is by no means sufficient merely to take photographs of the Sun with the spectroheliograph. In order to extend greatly the range of the attack, and also to explain the spectroheliograph results, simultaneous observations, both visual and photographic, with other instruments are essential. For example, while a photograph is being taken with the spectroheliograph, exposures on the spectrum of the region under investigation, for the purpose of showing the widened lines in Sun-spots as well as the motions in the line of sight of the calcium vapor in the flocculi, should be provided for. These must be made with an instrument of sufficient dispersion to permit the photographs to be measured with high precision. At the same time, large scale photographs of the photosphere and spots, made by direct photographic methods, are needed for comparison with the spectroheliograph results. Many bolometric studies are also required, as well as numerous other investigations which will suggest themselves to the reader. The essential point is that a *simultaneous* attack should be made on solar phenomena with a series of powerful instruments, each designed to answer definite questions, and thus to furnish some of the material that will be required for solving solar problems.

But such an attack, comprehensive as it might be made, would be greatly hampered if the atmospheric conditions were not favorable. The difference between the effects of good and bad seeing may be seen by comparing the blurred photograph reproduced in Fig. 1, Plate VII, which was the best that could be obtained at the time, with the (larger scale) photograph reproduced in Fig. 3, Plate IV, which was made with precisely the same instruments and adjustments at a time when the conditions were unusually good. If such conditions as these latter could be had day after day for long periods of time, with occasional periods of even finer definition, many questions now out of reach could be solved.

A report on the instrumental and atmospheric conditions needed in future work on the Sun may be found in the forthcoming *Year Book* (No. 2) of the Carnegie Institution.

OCTOBER, 1903.

DESCRIPTION OF THE PLATES

PLATE I

The Rumford spectroheliograph, attached to the forty-inch Yerkes refractor. The shaft which is driven by the declination motor may be seen at the right. It carries a grooved pulley near its lower end, connected with a similar pulley at the end of the camera box by means of a round leather belt. On the same shaft with this second pulley is a spur gear, which engages with the two gears on the projecting ends of the screws that pass through the camera box. The keys used to operate the split-nuts that clamp the plate-carriage to the screws, the windows for observing the spectrum at the middle and at the ends of the second slit, and the screw-drivers employed to push forward the plate-holder after the slide is withdrawn, are on the top of the camera box. At the left end of the box may be seen the door through which the plate-holder is inserted, and the narrow sliding door in its outer face through which the slide is withdrawn, as well as the micrometer heads of the screws for controlling the width of the second slit and for moving it as a whole. The first slit, at the end of the collimator, is almost hidden from view by the metallic screen required to shield its mounting from the great heat of the solar image. Light reaches the first slit through a long narrow opening in this screen. Mounted on four posts above the screen, at such a height as to lie in the visual focal plane when the first slit is at the focus for the K line, is a narrow metallic plate, on which a line is drawn in the direction of dispersion. During an exposure, the limb of the Sun is made to follow this line. At the end of the electric cable may be seen the switches used for operating the declination motor, and (just below) the rod with which the mirror in the prism box is rotated. The interior of the prism box is shown in Fig. 1, p. 8.

PLATE II

FIG. 1.—Full-size reproduction of a photograph of the H and K lines in the solar spectrum, made with the curved first slit. The two curved slits regularly employed with the spectroheliograph to eliminate distortion of the solar image have a radius of 522 mm, equal to that of the curved lines here shown.

FIG. 2.—The K line on the solar disk and in the chromosphere at the limb (radial slit). The bright reversals (K_2) are due to the flocculi. Where faculæ are present the continuous spectrum is more or less strengthened.

FIG. 3.—H and K lines on the solar disk and in the chromosphere (radial slit).

FIG. 3*a*.—Shows H_3 and K_3 (very faintly) in a prominence.

FIG. 4.—Reversals of the H and K lines in the electric arc, showing the decrease in width from the inner (dense) to the outer (rare) calcium vapor.

Fig. 5.—Minute calcium flocculi, resembling the granulation of the photosphere. The squares are $10''$ of arc on a side.

PLATE III

Entire disk of the Sun, as photographed 1903, August 12, 8^h 52^m C.S.T. with the H_2 line. Same size as original negative. The squares of the half-tone screen are too coarse to permit the smallest details to be shown.

PLATE IV

Fig. 1.—Low level (H_1) section of calcium flocculi, showing how these flocculi appear to be made up of vertical columns of calcium vapor.

Fig. 2.—High level (H_2) section of the same flocculi, showing (faintly) how the vapor columns seem to be bent over at the summit, as well as expanded.

Fig. 3.—Minute calcium flocculi, H_2 level, showing their normal appearance under excellent conditions of seeing.

PLATE V

Fig. 1.—For this photograph the second slit was set on the continuous spectrum at λ 3924. Consequently no flocculi are shown, though the faculæ are faintly visible. The forms of the latter should be compared with those of the flocculi in the other figures.

Fig. 2.—Low K_1 level. Slit set at λ 3929. This shows the dense calcium vapor not far above the photosphere. Compare with Fig. 1, and note that even at this low level the calcium vapor overhangs, and sometimes completely covers small spots.

Fig. 3.—Higher K_1 level. Slit at λ 3932. Though taken before the photographs reproduced in Figs. 1 and 2, this picture further emphasizes the differences noted at lower levels. The fact that the changes are progressive largely eliminates the time element, which might otherwise be suspected of causing the observed differences. As a matter of fact, these flocculi are quiescent and slowly changing, differing very decidedly from eruptive phenomena.

Fig. 4.—K_2 level. Slit at λ 3933.8. Here the calcium vapor is very brilliant, and covers a larger area. The photograph contains distinct evidence of dark absorbing masses at higher levels. Perhaps the best instance of this is the dark tongue which runs somewhat north of west from the small spot south preceding the largest one of the group. This tongue seems to form a part of an extensive dark area, which completely surrounds the bright flocculi of the group.

PLATE VI

A series of photographs, similar to those in Plate V, showing the changes in the calcium flocculi at different levels above the photosphere. In Fig. 4 evidences may be seen of dark flocculi due to absorbing vapors at higher levels.

PLATE VII

Fig. 1.—Small bright flocculus at region where the spot group appeared later. This photograph was taken when the seeing was very poor, and when compared with such a photograph as that in Fig. 3, Plate IV, serves as an excellent illustration of the importance of good seeing.

Fig. 2.—The same region one day later.

Fig. 3.—The same region on the following day, showing the calcium vapor at the H_2 level.

Fig. 4.—Photograph of the low-lying H_1 vapor corresponding to Fig. 3.

PLATE VIII

Fig. 1.—Calcium flocculi surrounding a spot when near the east limb of the Sun. The strong dark regions in this photograph are due to too great contrast in the original, and not to dark calcium flocculi.

Fig. 2.—The same region about six hours later, as photographed with the $H\beta$ line. Near the spot the hydrogen immediately surrounding the spot appears to be bright, while an extensive dark hydrogen flocculus lies to the east, occupying approximately the same region as that of the bright calcium flocculus.

It should be noted that all the photographs of hydrogen flocculi are slightly distorted, owing to the fact that a straight first slit and a curved second slit are used with the grating.

Fig. 3.—Dark calcium flocculus, corresponding to the exceptionally dark hydrogen flocculus shown in Fig. 4, which represents the same region of the Sun. The contrast in Fig. 3 is rather too great, and some regions which might seem to resemble dark flocculi should appear much lighter.

PLATE IX

Fig. 1.—As remarked in the text, the contrast is too great in this photograph, and the appearance of the brighter regions is deceptive. In reality, the dark regions in general represent the hydrogen flocculi, though there may be a few places near the spot where bright flocculi are present.

Fig. 2.—The contrast in this photograph is more nearly what it should be, though the background is in general too bright. Some well-defined examples of bright hydrogen flocculi may be seen to the west of the spot, where small spots were developing at the time.

FIG. 3.—This cut represents more nearly the appearance of the dark hydrogen flocculi on the negatives. As the slit did not coincide with the $H\beta$ line throughout its length, the flocculi are not shown to the west of the spot. A small bright flocculus may be seen at the extreme edge of the figure on the left, adjoining the small spot.

FIG. 4.—The contrast here is rather too great, and for this reason the background appears too dark. The general character of the bright calcium flocculi is nevertheless fairly well shown. The bright tongue extending into the small spot on the left is eruptive in character, and corresponds with the bright hydrogen flocculus referred to in the description of Fig. 3.

PLATE X

FIG. 1.—Low-level photograph, showing the dense calcium vapor lying just above the photosphere. In this photograph very little of the penumbra is covered by the calcium vapor, but evidences may be seen, especially in the southern part of the penumbra of the largest spot, of the columns of vapor which are greatly developed at the higher levels.

FIG. 2.—In this photograph the calcium vapor is much better shown than in Fig. 1, and the beginnings of eruptive phenomena have become more distinctly evident.

It is to be understood that although the changes going on in the eruptive phenomena of the spot group prevent a perfect comparison of all the details of the successive photographs in this and the subsequent series, the large masses of flocculi change so slowly in form that they may be compared without danger of serious error. In general, the differences between the successive pictures are therefore due to differences in the extent and brightness of the vapor at different levels, rather than to changes in form which have taken place between exposures. In order to render possible a satisfactory comparison of the high- and low-level flocculi surrounding this spot, the matched pair of photographs, reproduced in Plate XV, is given for examination with the stereoscope.

PLATE XI

FIG. 1.—This photograph, which represents the high-level calcium vapor, should be compared with Figs. 1 and 2, Plate X. It will be seen that at this level the penumbra is almost completely covered, while many of the smaller spots are blotted out. There are also distinct evidences of dark flocculi, due to absorbing vapors at still higher levels. The illustration necessarily fails to indicate the brilliancy of the brightest eruptive phenomena, which on the original negatives are easily distinguished from the ordinary flocculi.

FIG. 2.—This photograph, which shows the hydrogen flocculi surrounding the spot group, should be compared with Fig. 1. The brighter regions are in most cases eruptive. In general, the hydrogen flocculi in the less disturbed regions are dark, though they may perhaps be bright or neutral where they overhang the penumbra, and cover some of the smaller spots of the group.

PLATE XII

The photographs reproduced in this plate represent the low- and medium-level flocculi surrounding the spot group, as they appeared on October 10. The changes in the group may be seen by comparing these photographs with those given in Plate X.

PLATE XIII

FIG. 1.—The difference in level between Fig. 2, Plate X, and Fig. 1, Plate XI, is too great to permit of a satisfactory study of the changes in form of the flocculi at different heights above the photosphere. In the present series it is fortunately possible to give an intermediate step, obtained by setting the second slit immediately outside of H_2; the level shown therefore lies between that of Fig. 2, Plate XII, and that of Fig. 2, Plate XIII.

FIG. 2.—This photograph, although the same as that reproduced in Plate XIV, is given here in the endeavor to bring out the bright eruptive tongues, which in Plate XIV are hardly to be distinguished from the less brilliant flocculi. The abnormally dark background necessarily results from the deep printing required to show the exceedingly brilliant details. For a general view of the flocculi at this level reference must be made to Plate XIV.

PLATE XIV

This photograph belongs to the same series reproduced in Plates XII and XIII. It represents the high-level calcium vapor photographed with the H_2 line, and is made from the same negative reproduced in Fig. 2, Plate XIII. By comparing this plate with Fig. 1, Plate XIII, the presence of dark flocculi, due to absorbing vapors at higher levels, may be noticed. It should be remarked that a slight swaying of the telescope at the moment when the north preceding spot of the group was passing over the slit of the spectroheliograph has produced a certain small distortion of the details, in a narrow band extending through the small spot in the upper part of the figure.

PLATE XV

In comparing the photographs corresponding to different levels a double stereopticon is used, by which two negatives can be projected upon a screen, where the images are exactly superposed. The method has proved so instructive that it has seemed desirable to provide with this paper a simple means of accomplishing the same result. Accordingly, a pair of high- and low-level photographs has been arranged for use with the stereoscope. It is to be understood that no stereoscopic effect in the ordinary sense will be obtained in examining these photographs. The purpose of using the stereoscope is merely to allow the images to be superposed, thus permitting them to be seen at the same point in rapid succession by quickly moving a card so as to cover alternately the two lenses of the stereoscope. In this way the same region of the Sun may be examined, first as it appears at the low level of the denser calcium vapor, and then as it appears at the higher level of the rarer vapor. Thus the manner in which the calcium flocculi overhang the penumbra, and sometimes the umbra of spots, and the absence at the lower level of the dark structures shown in certain parts of the high-level picture, can be observed. This method of comparison also gives an excellent means of detecting small changes in the form of the flocculi, as shown by photographs corresponding to the same level, but taken at different times.

PLATE II

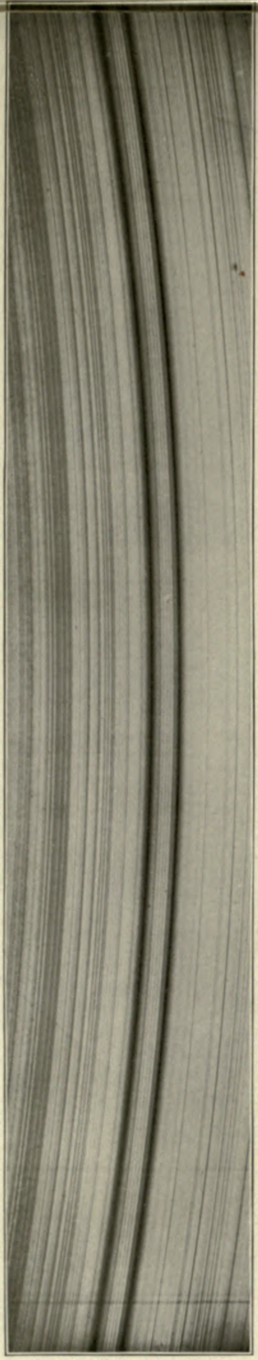


Fig. 1. Curvature of Lines in the Spectroheliograph

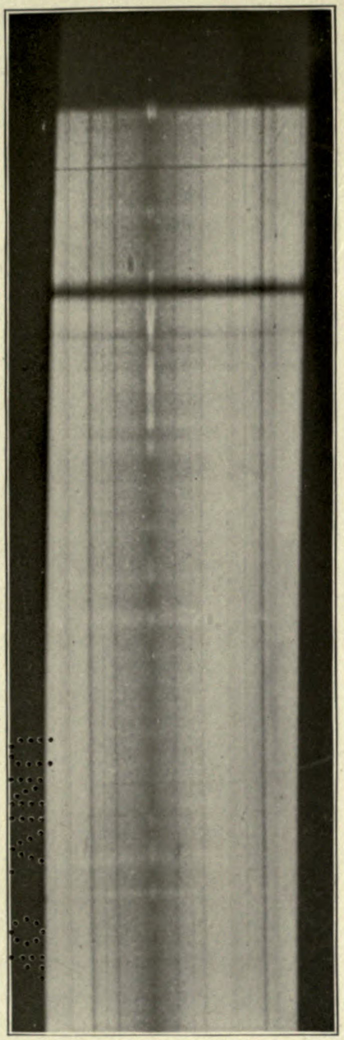


Fig. 2. K Line on the Disk and at the Limb

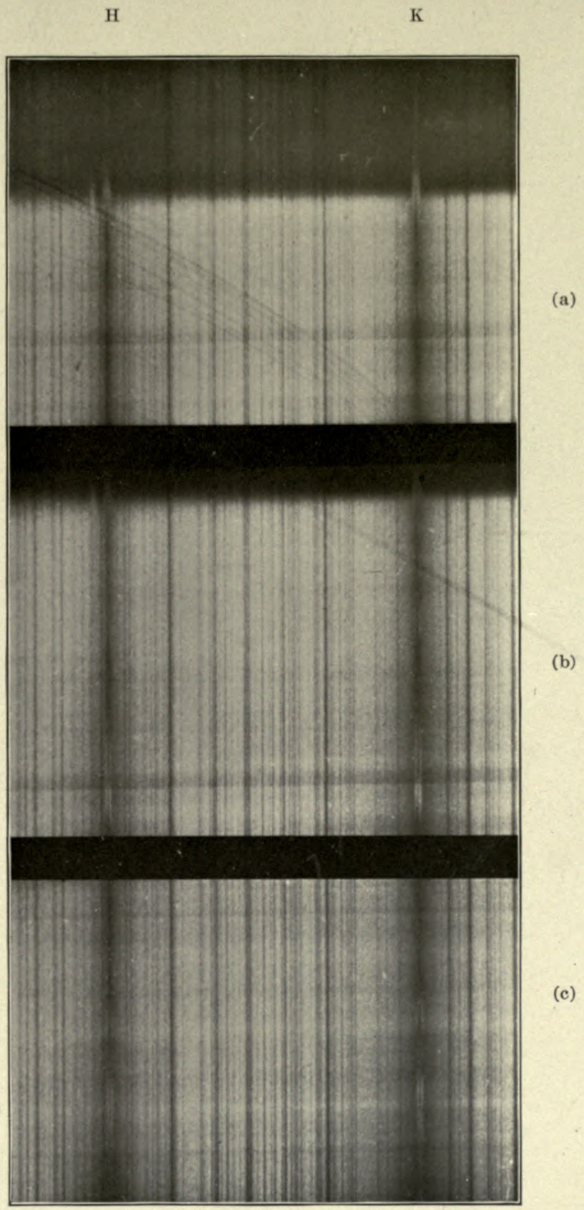


Fig. 3. H and K Lines on the Disk, in the Chromosphere, and in a Prominence (a)

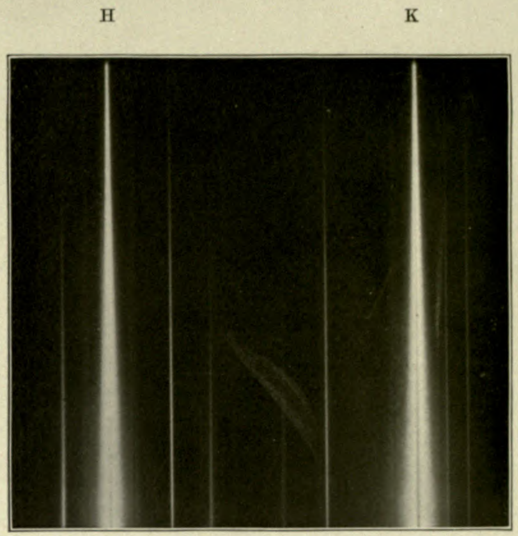


Fig. 4. H and K Lines in Electric Arc Showing Reversals

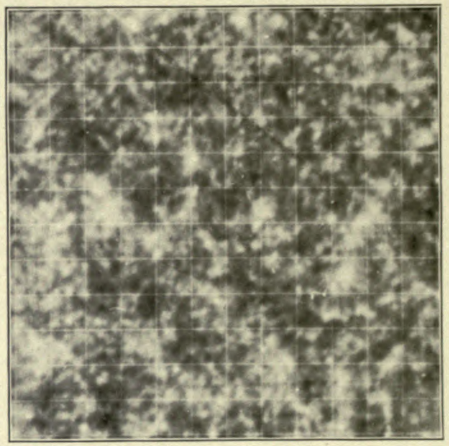
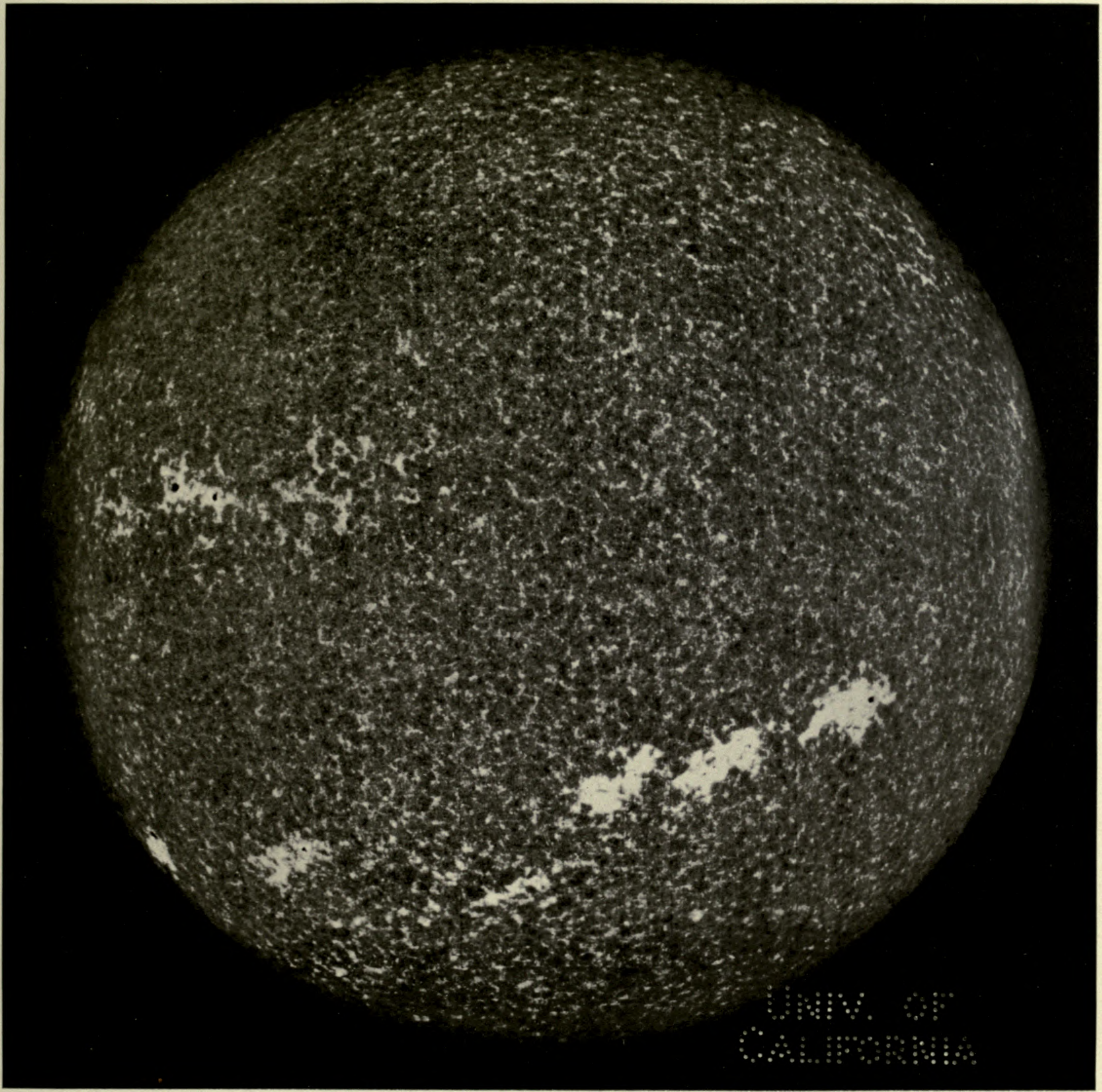


Fig. 5. Minute Calcium Flocculi (H_2) The Squares are 10″ on a Side



THE SUN, SHOWING THE CALCIUM FLOCCULI (H_2 LEVEL). 1903, AUGUST 12, $8^h 52^m$. C. S. T.

PLATE IV

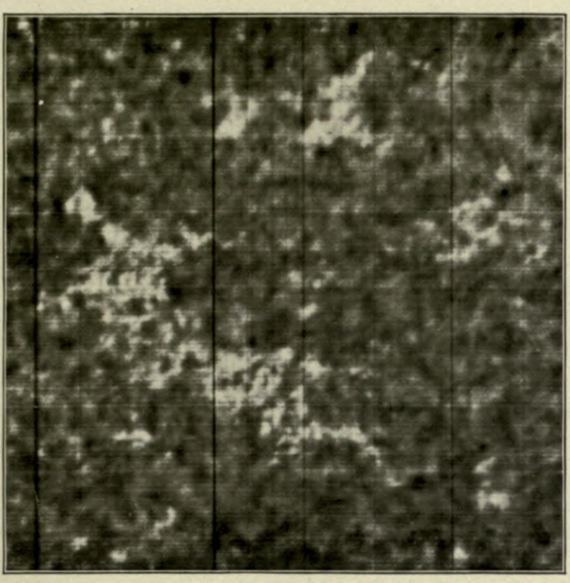


FIG. 1. $3^h 40^m$. LOW H_1 LEVEL
Slit at $\lambda 3962$

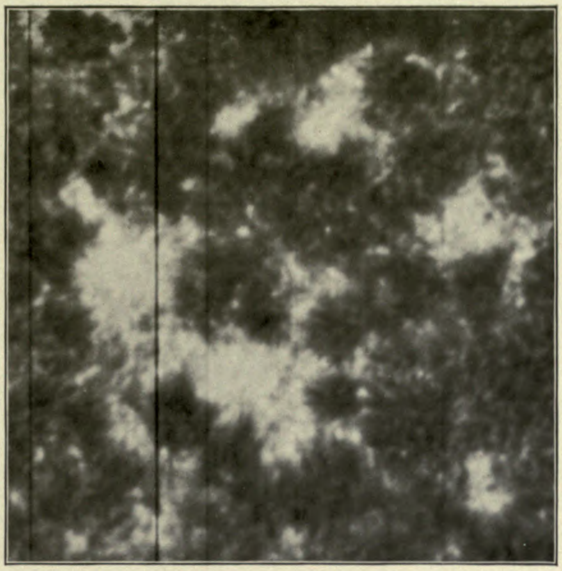


FIG. 2. $3^h 31^m$. H_2 LEVEL
Slit at $\lambda 3968.6$. Same Region as FIG. 1

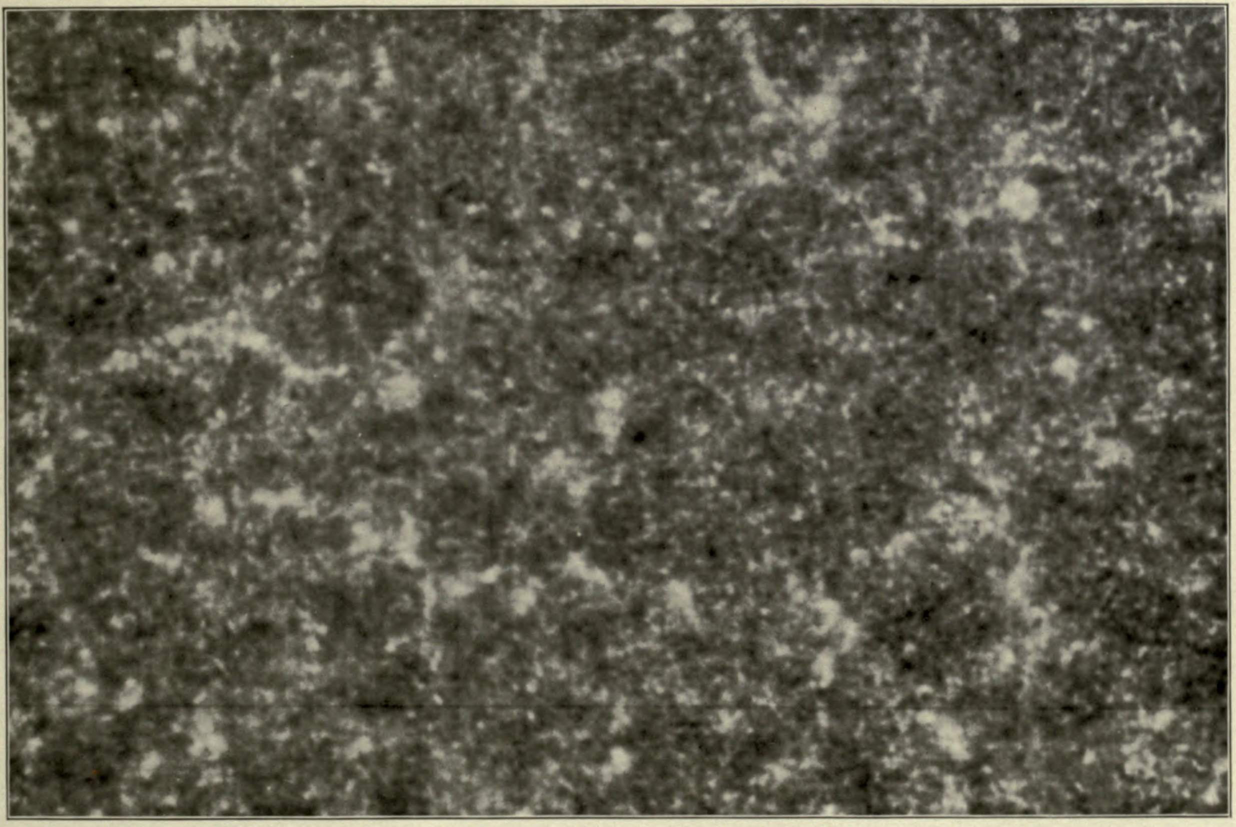


FIG. 3. $3^h 31^m$. GENERAL APPEARANCE OF SUN'S DISK AT H_2 LEVEL

MINUTE STRUCTURE OF THE CALCIUM FLOCCULI, 1903, SEPTEMBER 22
Scale: Sun's Diameter = 0.890 Meter

PLATE V

N

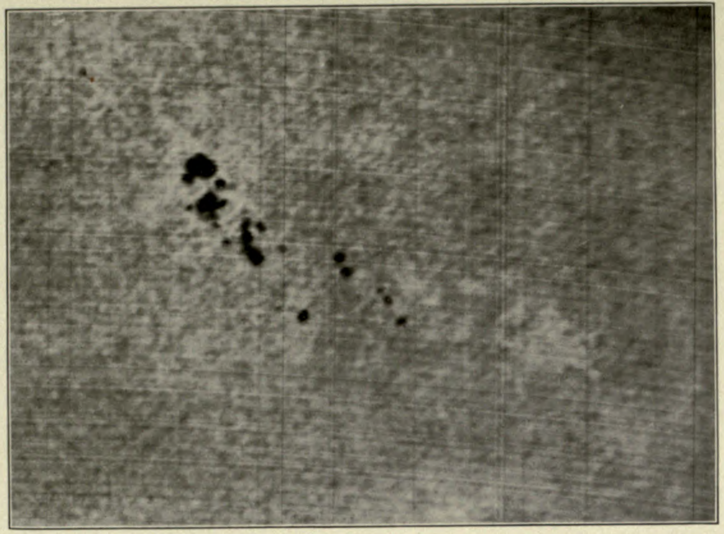


FIG. 1. 11h 32m. FACULÆ
Slit on Continuous Spectrum at λ 3924

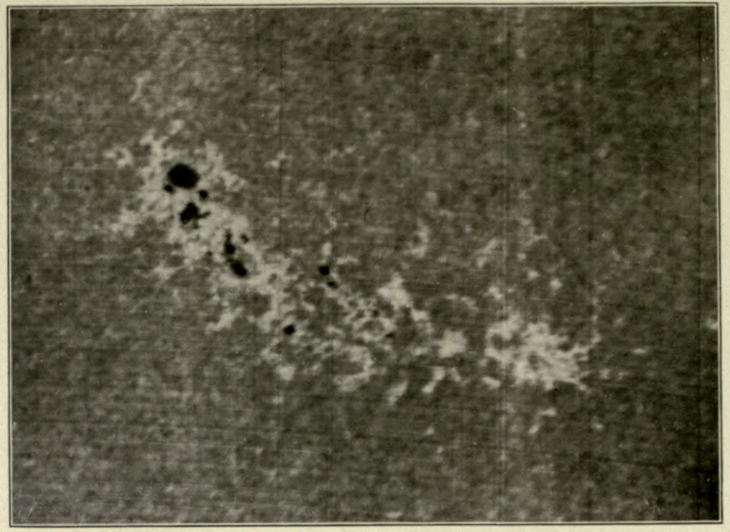


FIG. 2. 11h 22m. CALCIUM FLOCCULI, LOW K_1 LEVEL
Slit at λ 3929

E

W

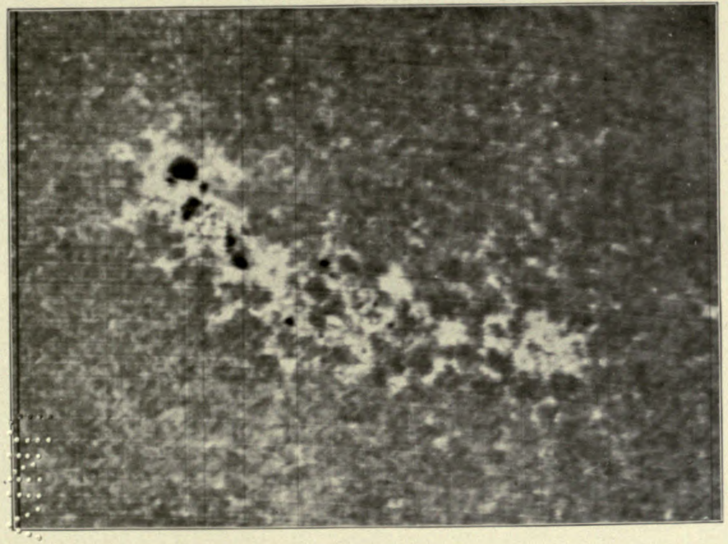


FIG. 3. 10h 28m. CALCIUM FLOCCULI, HIGHER K_1 LEVEL
Slit at λ 3932

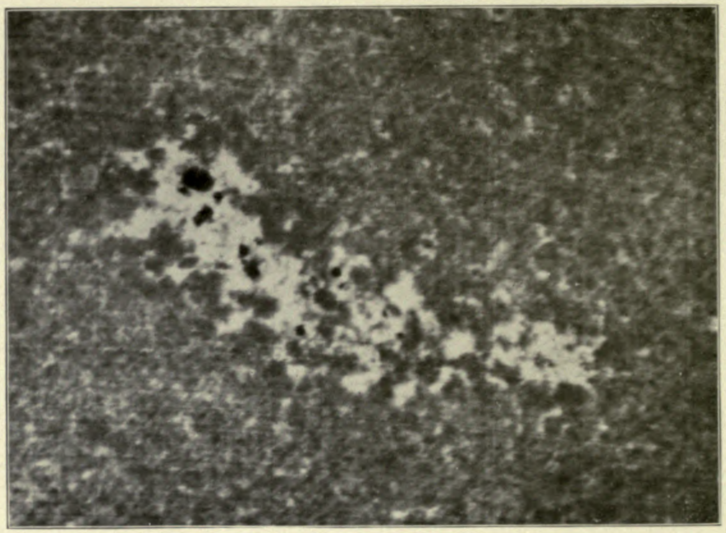


FIG. 4. 11h 11m. CALCIUM FLOCCULI, K_2 LEVEL
Slit at λ 3933.8

S

FACULÆ AND SECTIONS OF CALCIUM FLOCCULI AT DIFFERENT LEVELS, 1903, APRIL 29
Scale: Sun's Diameter = 0.280 Meter

PLATE VI

N

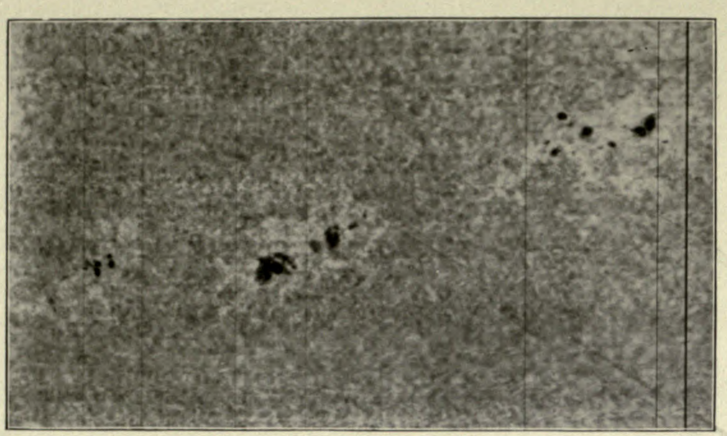


Fig. 1. 3h 47m. Faculæ
Slit Set on Continuous Spectrum at λ 3921

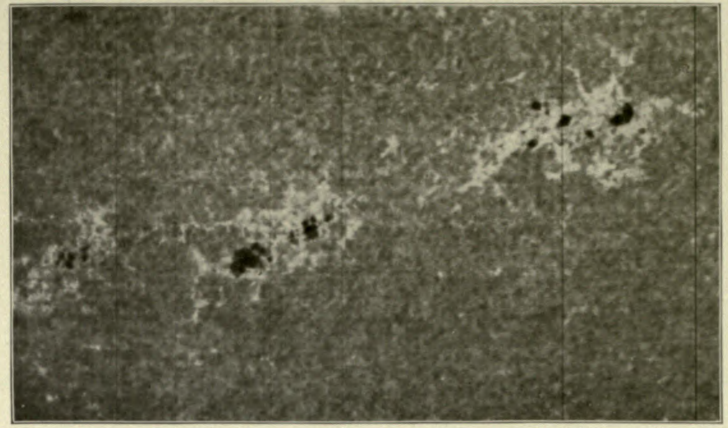


Fig. 2. 4h 0m. Calcium Flocculi, Low K_1 Level
Slit at λ 3929

E

W

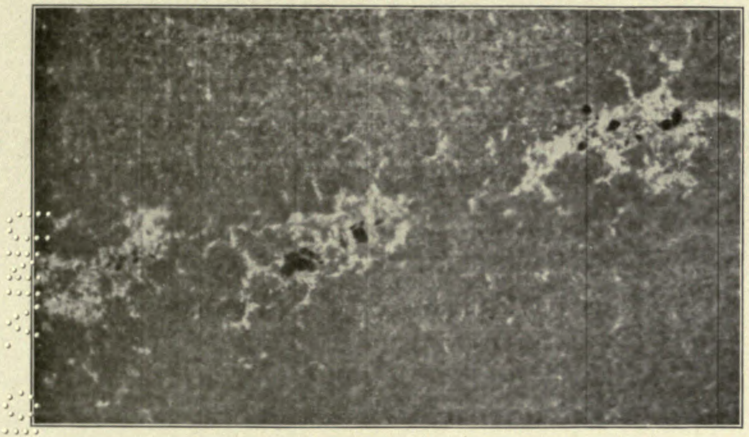


Fig. 3. 3h 55m. Calcium Flocculi, Higher K_1 Level
Slit at λ 3932

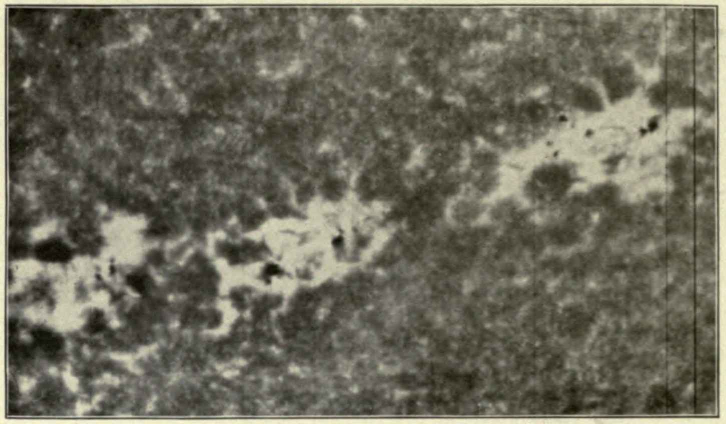


Fig. 4. 4h 06m. Calcium Flocculi, K_2 Level
Slit at λ 3933.8

S

FACULÆ AND SECTIONS OF CALCIUM FLOCCULI AT DIFFERENT LEVELS, 1903, AUGUST 10
Scale: Sun's Diameter = 0.295 Meter

PLATE VII

N

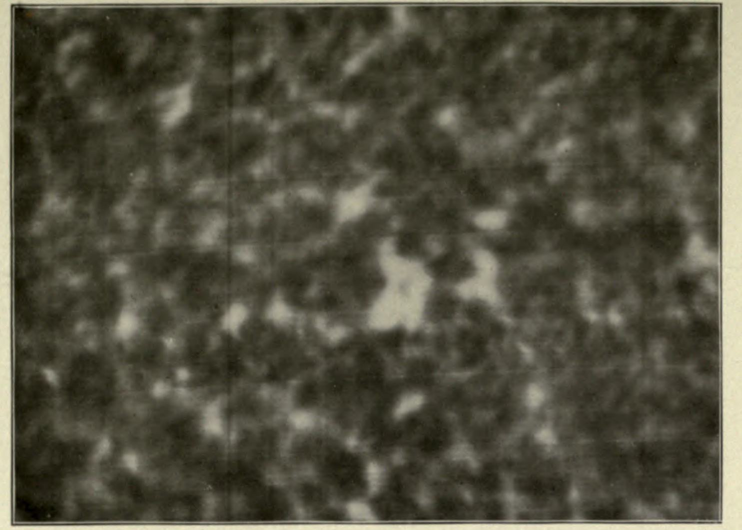


Fig. 1. July 23, $10^h 19^m$. High Level
Slit Set on K_2 (λ 3933.8)

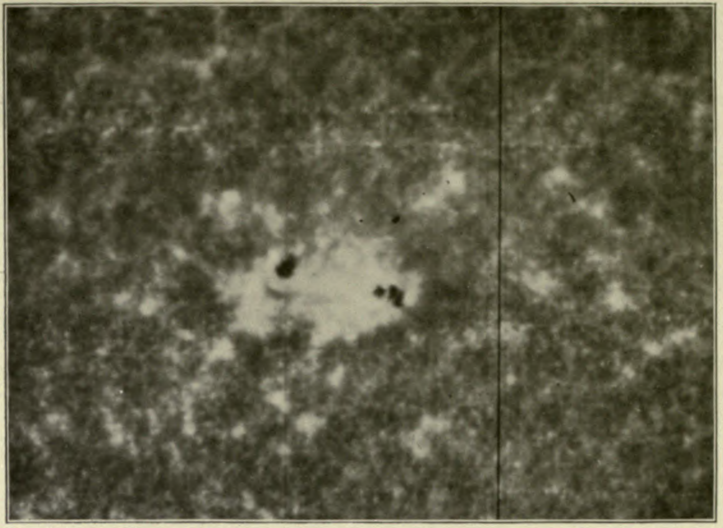


Fig. 2. July 24, $9^h 27^m$. High Level
Slit Set on H_2 (λ 3968.6)

E

W

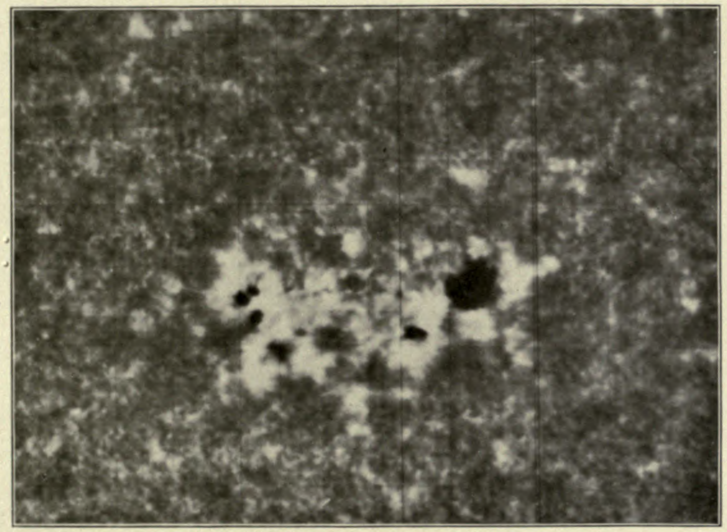


Fig. 3. July 25, $9^h 26^m$. High Level
Slit Set on H_2 (λ 3968.6)

S

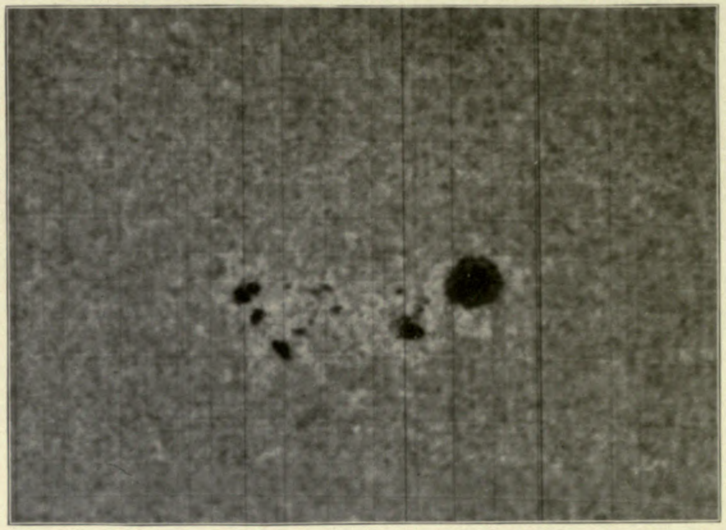


Fig. 4. July 25, $8^h 52^m$. Low Level
Slit Set on H_1 (λ 3962)

RAPID DEVELOPMENT OF SPOT-GROUP AND CALCIUM FLOCCULI
Scale: Sun's Diameter = 0.680 Meter

PLATE VIII

N

E

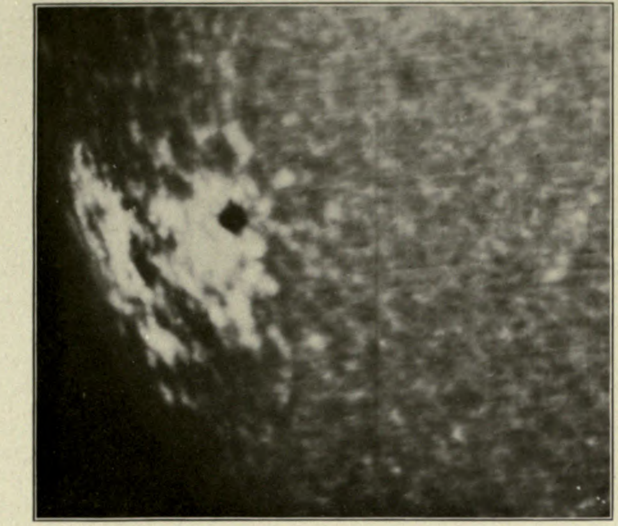


FIG. 1. JULY 2, 9^h 39^m. CALCIUM FLOCCULI, K_2 LEVEL
Slit at λ 3933.8

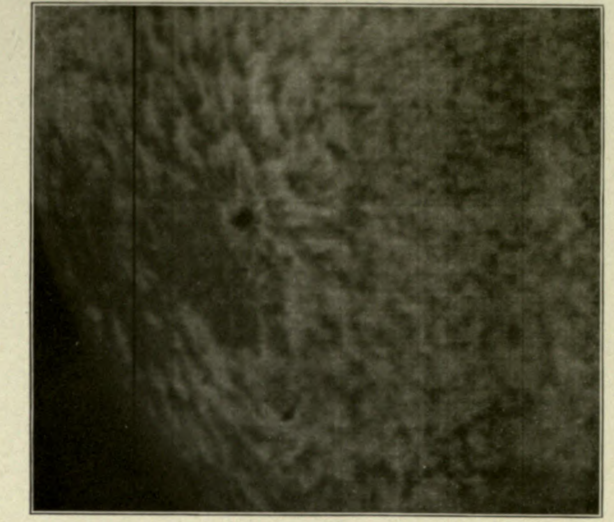


FIG. 2. JULY 2, 3^h 40^m. HYDROGEN FLOCCULI
Slit at Center of *Hβ*

W

Scale: Sun's Diameter = 0.335 Meter

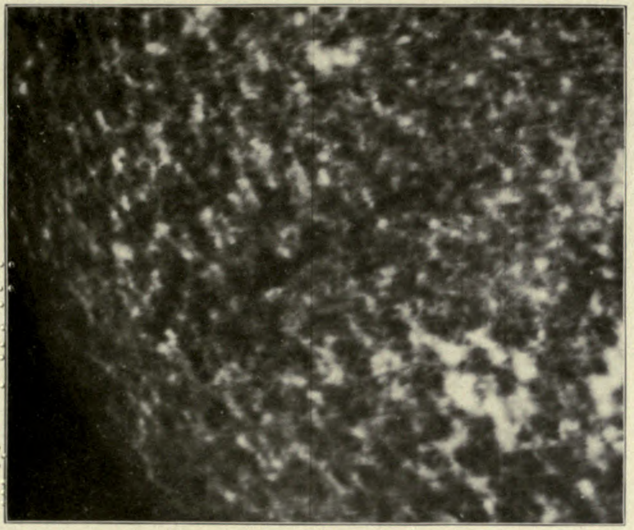


FIG. 3. JUNE 17, 9^h 08^m. DARK CALCIUM FLOCCULUS
Slit at λ 3933.8

S

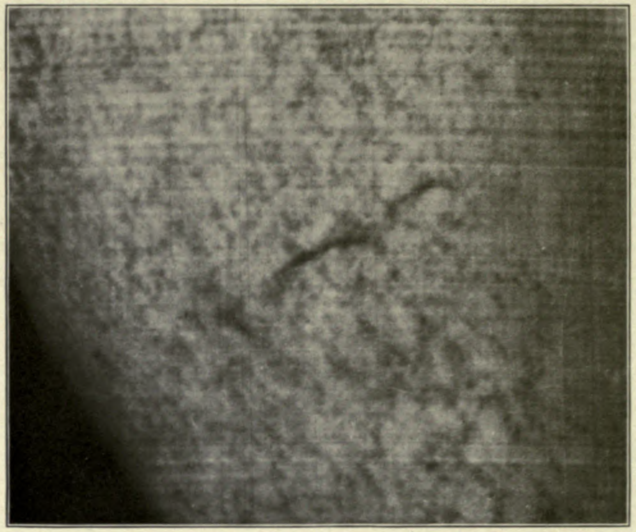


FIG. 4. JUNE 17, 10^h 18^m. STRONG HYDROGEN FLOCCULUS
Slit at Center of *Hβ*. (Compare with Fig. 3)

Scale: Sun's Diameter = 0.350 Meter

COMPARISON OF CALCIUM AND HYDROGEN FLOCCULI

PLATE IX

N

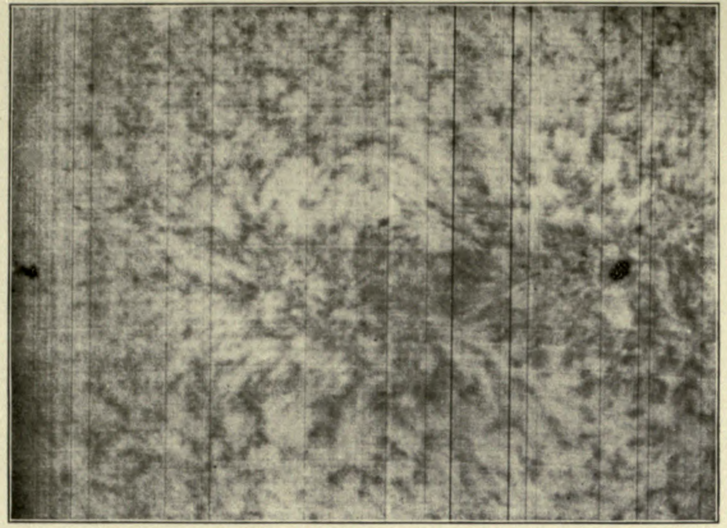


Fig. 1. $9^h\,39^m$. Hydrogen Flocculi
Slit at Center of $H\beta$

E

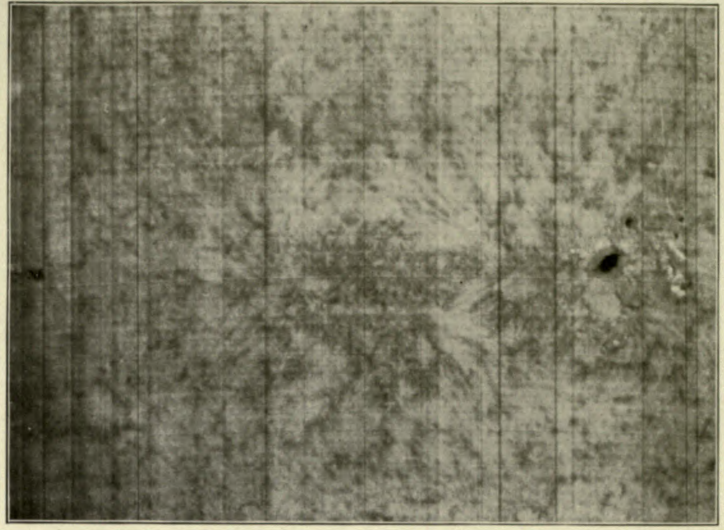


Fig. 2. $11^h\,0^m$. Hydrogen Flocculi
Slit at Center of $H\gamma$. (Bright eruptive flocculi west of spot)

W

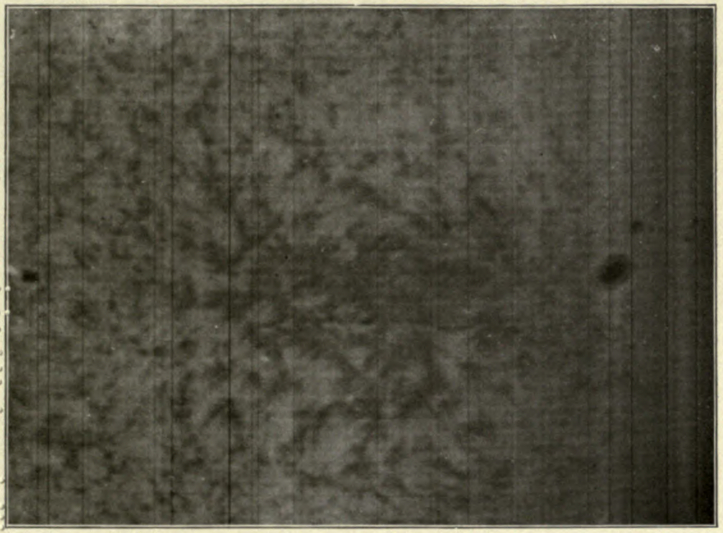


Fig. 3. $2^h\,50^m$. Hydrogen Flocculi
Slit at Center of $H\beta$

S

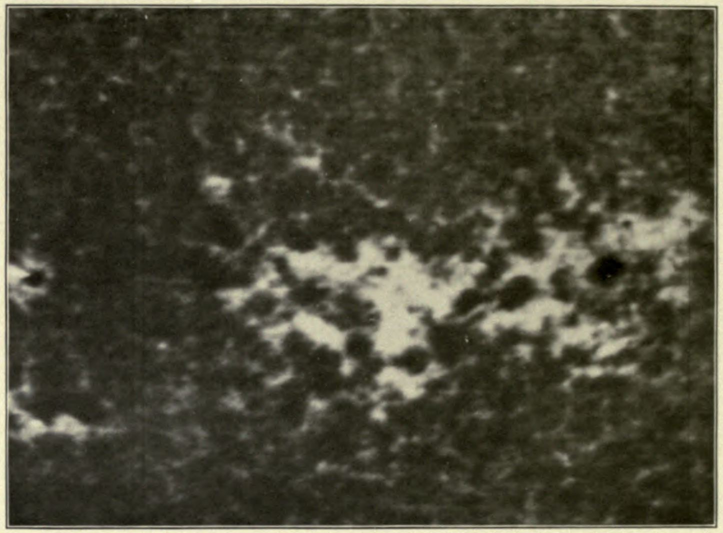


Fig. 4. $3^h\,57^m$. Calcium Flocculi, K_2 Level
Slit at $\lambda\,3933.8$

HYDROGEN AND CALCIUM FLOCCULI, 1903, JULY 7
Scale: Sun's Diameter = 0.290 Meter

PLATE X

N

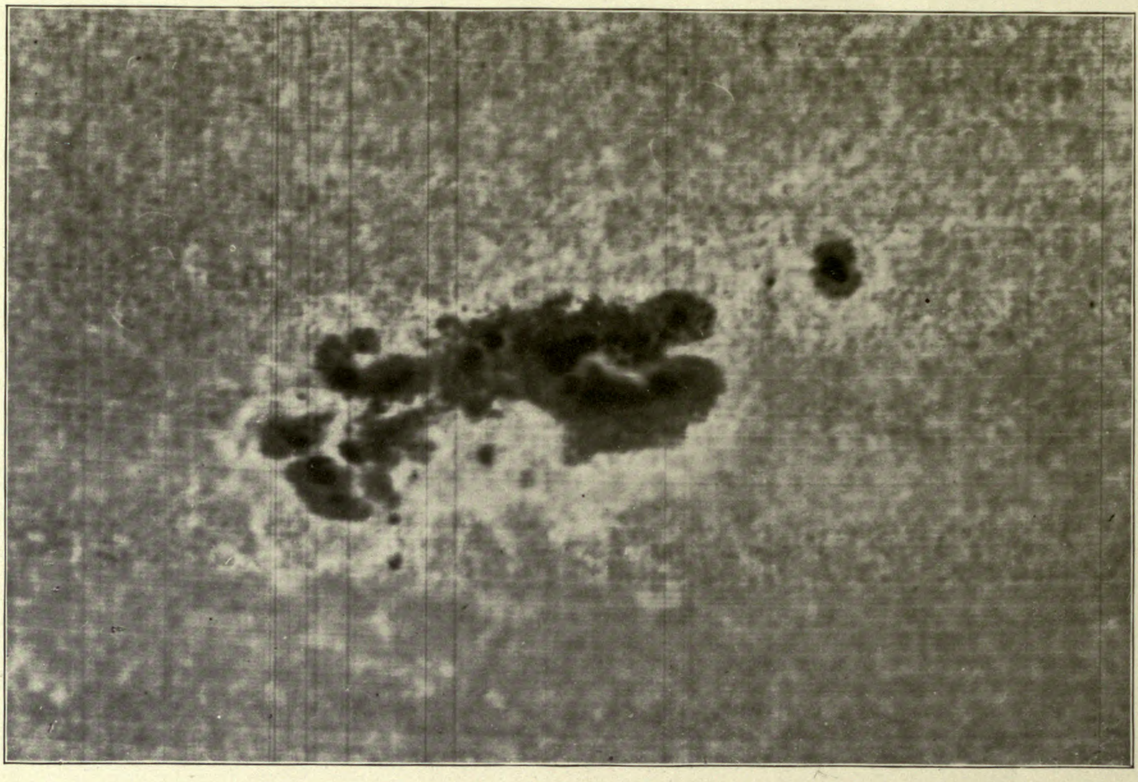
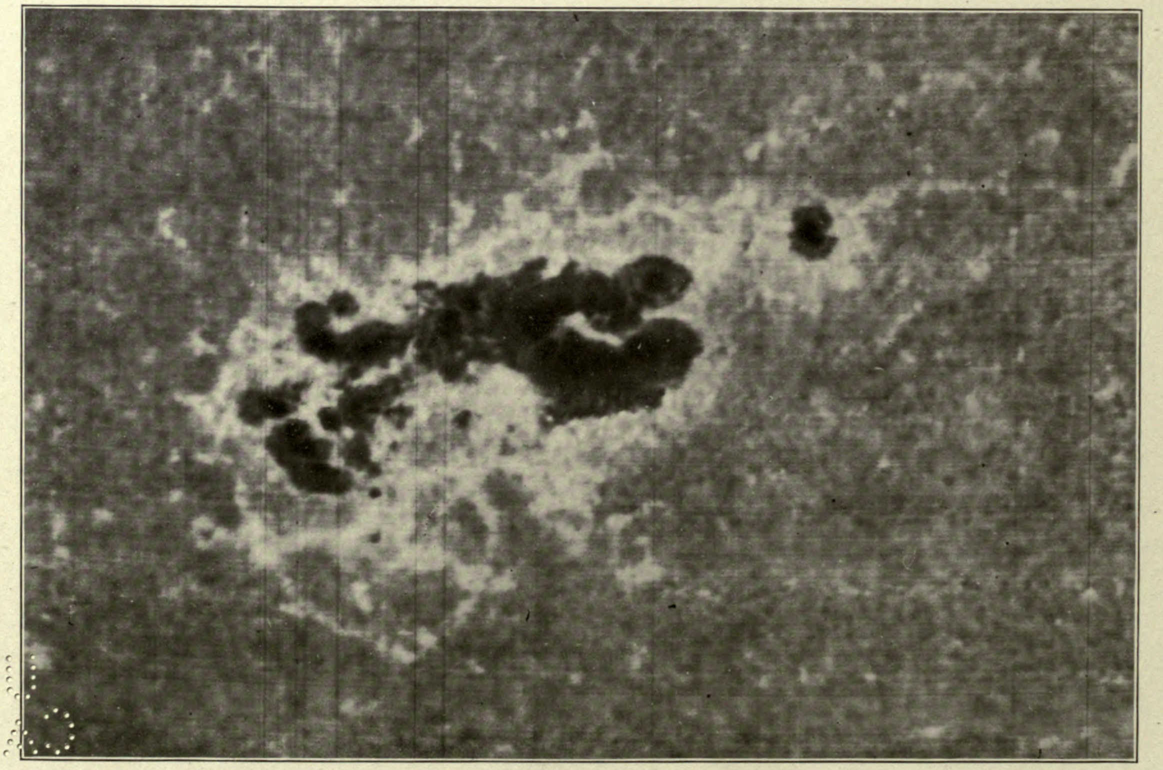


FIG. 1. OCT. 9, $3^h 42^m$. CALCIUM FLOCCULI, LOW H_1 LEVEL
Slit at λ 3962

E

W



S

FIG. 2. OCT. 9, $3^h 43^m$. CALCIUM FLOCCULI, MIDDLE H_1 LEVEL
Slit at λ 3966

THE GREAT SUN-SPOT OF OCTOBER, 1903
Scale: Sun's Diameter = 0.550 Meter

PLATE XI

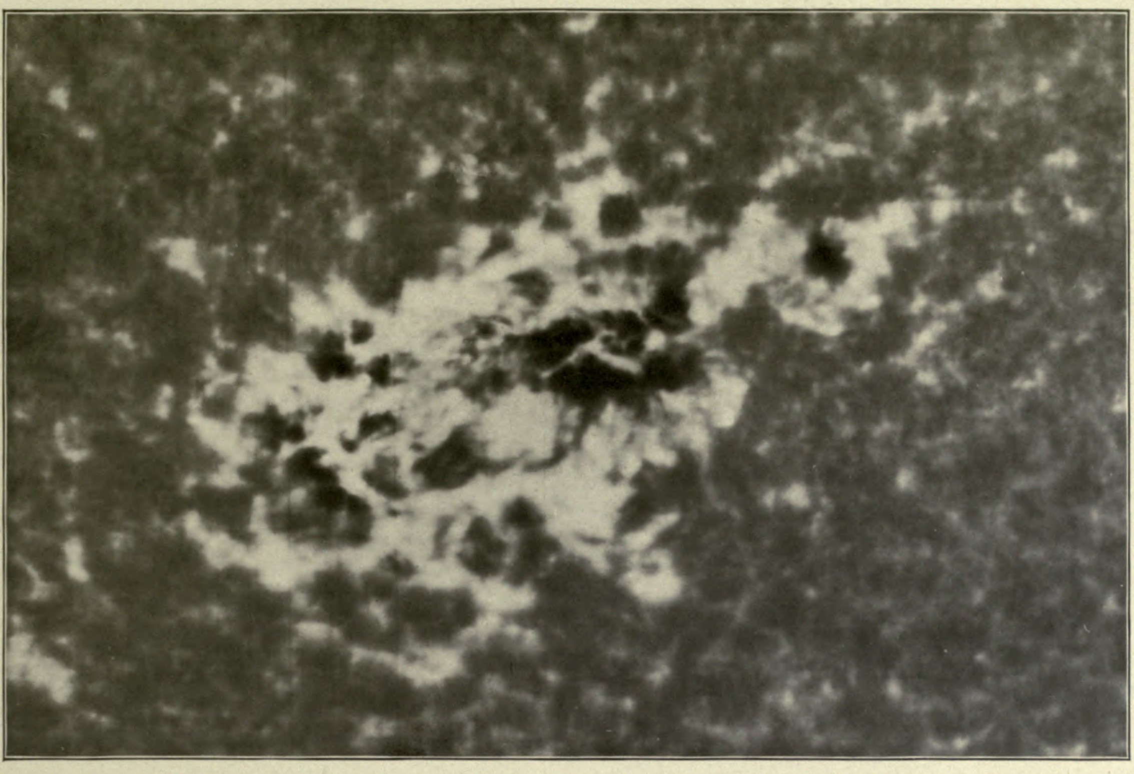


FIG. 1. OCT. 9, $3^h 30^m$. CALCIUM FLOCCULI, H_2 LEVEL
Slit at λ 3968.6

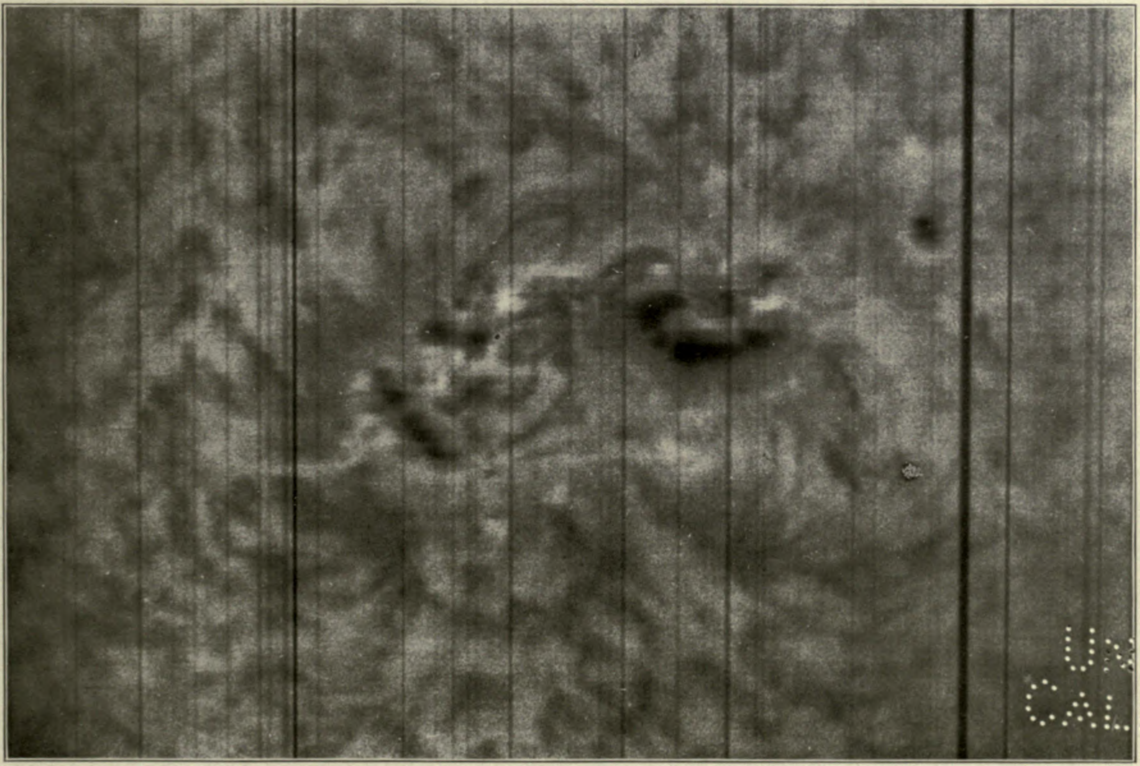
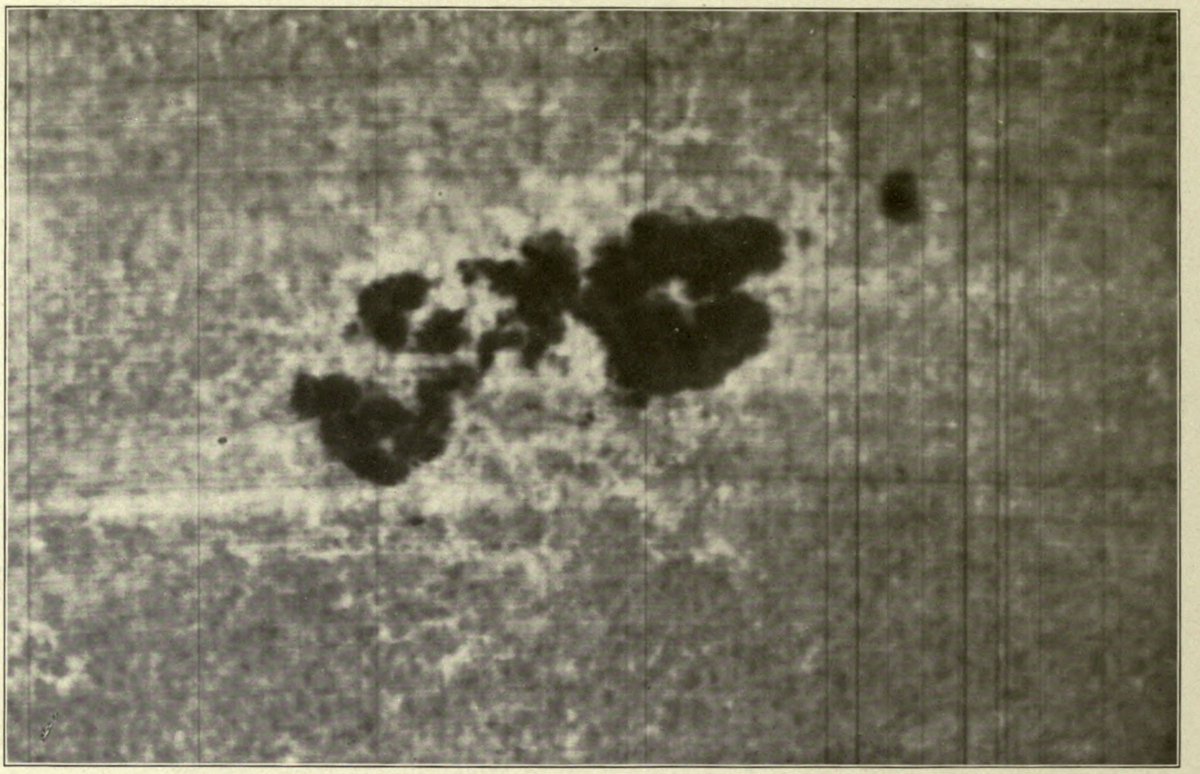


FIG. 2. OCT. 9, $1^h 04^m$. HYDROGEN FLOCCULI
Slit Set on $H\beta$

THE GREAT SUN-SPOT OF OCTOBER, 1903

PLATE XII

N

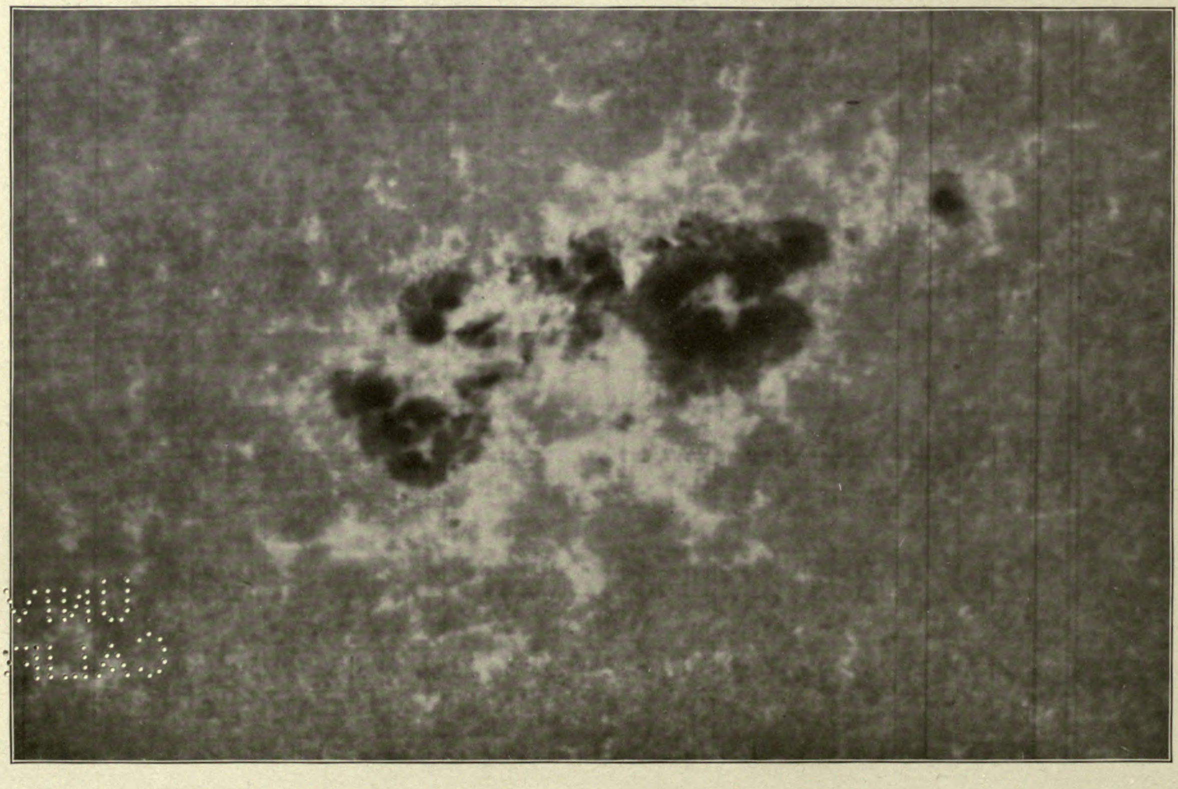


E

Fig. 1. Oct. 10, $8^h 58^m$. Calcium Flocculi, Low H_1 Level

Slit at λ 3962

W



S

Fig. 2. Oct. 10, $9^h 39^m$. Calcium Flocculi. Middle H_1 Level

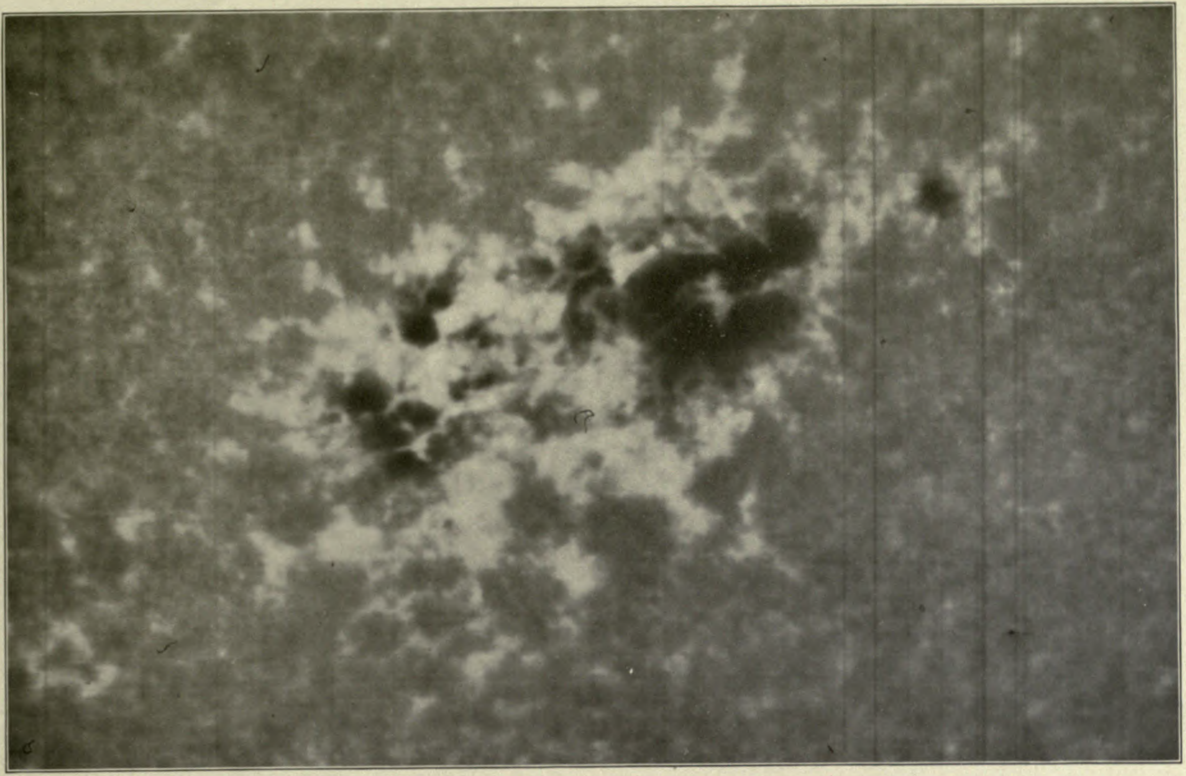
Slit at λ 3966.5

THE GREAT SUN-SPOT OF OCTOBER, 1903

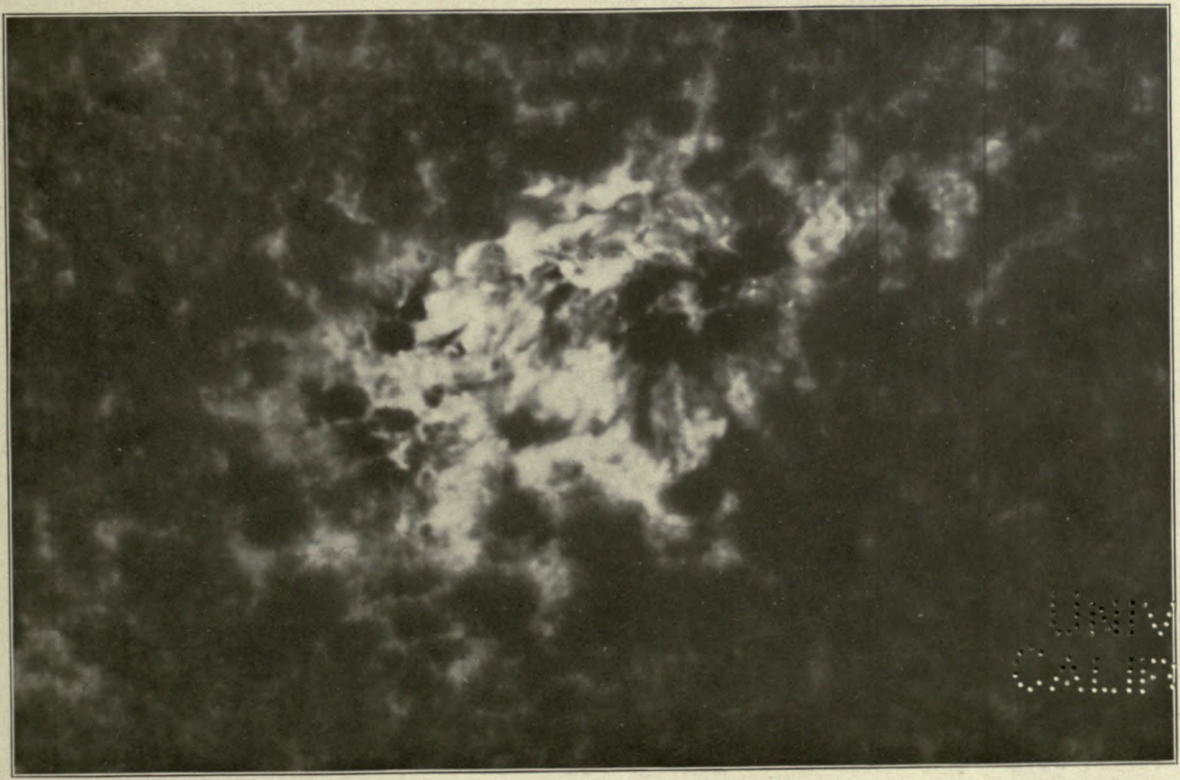
Scale: Sun's Diameter = 0.565 Meter

PLATE XIII

N



E Fig. 1. Oct. 10, 10h 59m. Calcium Flocculi, High H_1 Level W
Slit at λ 3967.5

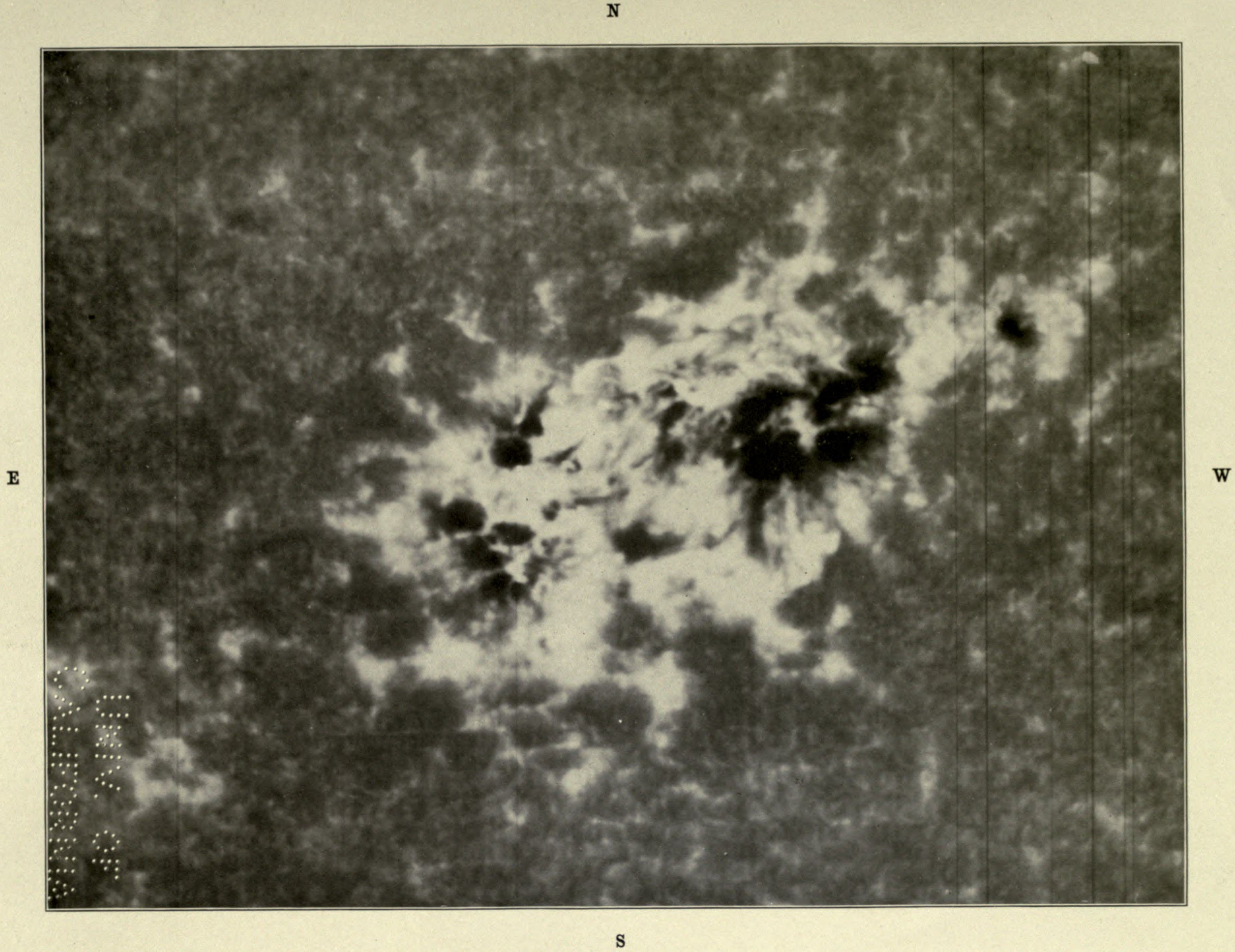


S

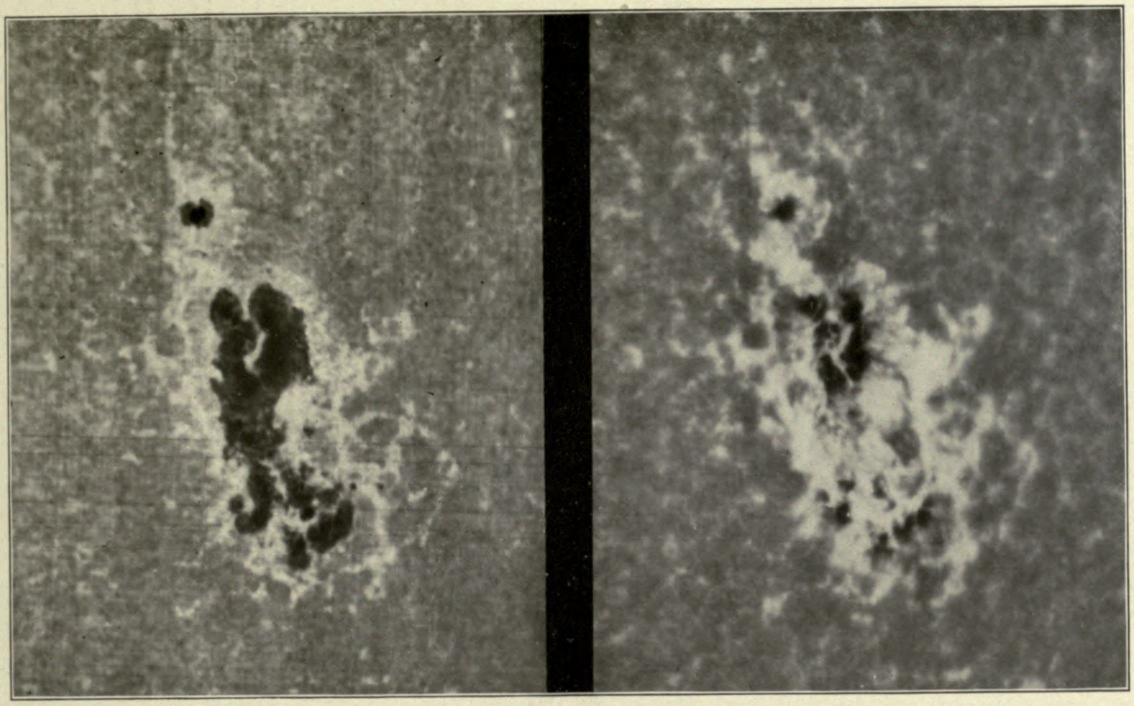
Fig. 2. Oct. 10, 9h 09m. Calcium Flocculi, H_2 Level
Slit at λ 3968.6

THE GREAT SUN-SPOT OF OCTOBER, 1903
Scale: Sun's Diameter = 0.565 Meter

PLATE XIV



THE GREAT SUN-SPOT OF OCTOBER, 1903. CALCIUM FLOCCULI, H_2 LEVEL
Slit at λ3968.6. Octber 10, $9^h 09^m$. Scale: Sun's Diameter = 0.725 Meter



Oct. 9, $3^h\,43^m$. Calcium Flocculi, Middle H_1 Level
Slit at λ 3966

Oct. 9, $3^h\,30^m$. Calcium Flocculi, H_2 Level
Slit at λ 3968.6

THE GREAT SUN-SPOT OF OCTOBER, 1903
For Comparison with the Stereoscope

8 | 1808
16
20
16
48